# INVESTIGATIONS OF AND INSTRUMENTATION FOR MEASURING PRESSURE DISTRIBUTIONS IN SOIL

By

Arthur Wiggins Cooper

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

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Approved by H. F. McColly

The development of a strain gage cell for measuring pressures in soil caused by surface loadings is described in detail. The pressure cell is two inches in diameter and three-fourths of an inch in thickness. It consists of a stainless steel disk (0.025 of an inch in thickness) soldered to a brass box with a removable bottom. Two active SR-4 strain gages are cemented to the underside of the stainless steel disk. Two "dummy" gages are cemented to the inside of the brass box. The gages make up the four arms of a Wheatstone bridge. When pressure is applied to the stainless steel disk it causes a change in resistance in the active gages. The voltage signal is amplified and indicated or recorded. The cell gives accurate pressure measurements when suspended in a homogeneous soil.

Comparative pressure measurements were made with the small pressure cell and a load cell (4 1/8 inches high, 1 3/4 inch in diameter, with a six inch diameter base). The load cell was found to give pressure readings two or more times as high as the small cell.

A small amount of work is reported using liquid-filled rubber pickups and a liquid pressure transducer. Rubber tubing pickups did not have a linear calibration while a rubber balloon did. All of the liquid-filled pickups indicate a low reading of pressure when used in soil.

The measured variation of soil pressure with depth under the center of the rear tire of a tractor is reported. This change in pressure with depth followed the same general pattern as values calculated by a theoretical formula developed by Froehlich.

A theoretical discussion is given of the effect of surface contact area on the pressure in the soil along the load axis of a uniformly loaded circular plate as calculated by Froelich's formula. The discussion points out that the pressure at various depths under the surface of the soil is a function of the total load and the surface contact area of the load. It is not a function of the unit pressure applied to the surface alone. For example, an 18-inch diameter plate applying a load of ten psi would cause a pressure of 4.6 psi at 15 inches depth in soil. A 12-inch diameter plate applying ten psi would cause a pressure of 2.6 psi at 15 inches depth. If the same total load that was applied to the 12-inch plate was applied to a circular plate having twice the area of the 12-inch diameter plate (17 inches in diameter), the unit surface load would be five psi, but the resulting pressure along the load axis 15 inches below the surface would be 2.1 psi as compared to the 2.6 psi for the 12-inch plate applying the ten psi at the surface.

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# VITA

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# INTRODUCTION

For many years agricultural workers have generally accepted the importance of the physical properties of soil to plant growth. A large portion of the statement, however, concerning this relationship has been vague, qualitative, and frequently unsupported by factual information. For this reason, a Joint Committee on Soil Tilth was established some years ago by the American Society of Agronomy and the American Society of Agricultural Engineers for the purpose of establishing methods and procedures for measuring and evaluating "soil tilth".

The following extracts are from reports of the Joint committee on Soil Tilth.

> 1943: No amount of empirical experimentation will tell us whether sub-surface tillage is superior to plowing, whether plowing is superior to disking, or what changes are desirable in the design of tillage machinery. Before we can make real progress we must know what soil physical state is desired for a given crop under specified climatic conditions. We must be able to measure the changes produced in soil tilth by our different management practices.

> 1944: The Committee has found that many research people desire to measure soil tilth, but no one seems to know how to do it. Unfortunately, the Committee cannot provide an exact yardstick.

> 1945: There has been considerable discussion of soil tilth over recent years. This Committee has reported annually that something ought to be done about

> it. Among other things we have suggested the establishment of a national tilth laboratory. Despite all that has been said and all that has been recommended, there has been very little done in the way of improving our situation with regard to measuring soil tilth and its effect upon plant growth. We believe the reason for this is that there is very little enthusiasm among research workers for the present methods of approach to the tilth problem that we are now making. It seems that it is going to be necessary for us to make some new approach.

As a result of the deliberations of this joint committee a monograph (30)[1] was prepared to meet a long-felt need among soil and plant scientists and agricultural engineers for a critical evaluation of the relation of soil physical conditions to plant growth. The monograph discusses: (a) soil as a physical system, (b) mechanical impedance and plant growth, (c) soil water and plant growth, (d) soil aeration and plant growth, and (e) soil temperature and plant growth. It was written by nine scientists and edited by B. T. Shaw.

In the epilogue of the monograph, Shaw states:

> Having read this far, the thoughtful reader may well be amazed that a plant is able to grow in such a complex environment. He doubtless has arrived at the conclusion of the authors; namely, that although we have some understanding and limited techniques for control of single factors affecting plant growth, we understand very little of the complex interrelationships among these factors, and hence are not in good position to modify them intelligently.

Later he states:

> During a given season, first one and then another of the physical factors may limit plant growth. For

[1]Numbers in parentheses refer to References Cited.

> example, a soil with a claypan may be slowly drained in the spring. Because the soil is nearly saturated with water, it warms up slowly. In addition to the unfavorable soil temperature, root growth may be limited also by lack of adequate quantities of soil air, because a large proportion of the pores are filled with water. As the season progresses, a shallow pattern of root growth is formed, whether root penetration is inhibited by mechanical impedance or by lack of aeration in the claypan. Still later in the season, lack of adequately distributed rainfall may result in soil moisture being limiting to the shallow rooted crop. Then, conceivably, saturation of the soil by a heavy rain still later on brings soil aeration back into play as the factor most seriously limiting plant growth at that time.

The writing of this monograph, published in 1952, was the last official act of the Joint Tilth Committee.

A number of soil and plant scientists and agricultural engineers, however, are still working on these problems. They are trying to determine the best physical properties of the soil for plant growth, and the methods of tillage and soil management practices to obtain these soil physical factors.

## Soil Compaction

One of the factors creating a soil physical condition which decreases plant growth is that of soil compaction, as described by Shaw in the case of the claypan soil. Soil compaction often reduces crop yields (3, 4, 14, 27). This problem is not new. Interest in subsoiling to break up compacted layers has varied periodically in the past 50 years. Recently there has been a revived interest among agricultural workers, including farmers as well as soil and plant scientists and agricultural engineers.

Reasons for Revived Interest in Soil Compaction and Subsoiling

1. The traffic over agricultural fields with tractors, implements, and trucks has increased rapidly in recent years. An example of increased traffic is spraying to control insects. In cotton, for instance, the farmer may spray five to ten times in a season to control insects. Also the total weight and in many cases the unit load of the traffic has increased. Spreading lime with trucks is a good example of this increased total and unit load. In addition to the weight of the truck it may be carrying three to five tons of lime when it goes on the field. The total load on the rear wheels of one of the largest wheel type tractors while plowing was measured and found to be over 9,000 pounds. One company now reports measuring 16,000 pounds on the rear wheels of one of their experimental tractors. Even though the extent of damage due to this traffic has not been evaluated it is an effective selling point for subsoiling and the farmers have become quite interested in this practice. Certainly the effect of this traffic on soil compaction should be studied and evaluated.

2. With increased power available in recent years it has been easier for the farmer to stir the surface of the soil. In numerous cases he has done this several times in the spring or fall to prepare what he considers a better seedbed and to kill weeds. Much of this stirring operation has been done with a disk harrow which packs the soil below the depth of penetration of the harrow (9). No matter what tool it is done with, in some soil types this stirring action aids in the formation of filter pans. These pans are formed by fine particles moving down to the bottom of the tilled area and filling the voids.

3. With increased power available it now costs the farmer less money and effort to accomplish subsoiling. He is much more willing to try it in hopes that it will increase yield from the land. Furthermore in some states Agricultural Conservation Payments made for subsoiling have increased interest in this practice.

4. In many cases subsoiling has increased the water intake of the soil, so that less moisture is lost due to runoff. On a few soil types substantial increases in yield have been obtained due to subsoiling.

5. The increased interest in deep fertilizer placement has caused an increased interest in deep tillage.

6. Some very tough soils are easier to plow in the spring if they are ripped with a deep tillage tool in the fall.

ASAE-SSSA Committee on Soil Compaction

Because of the recent interest in soil compaction and deep tillage a joint Soil Compaction Committee of the American Society of Agricultural Engineers, and of the Soil Science Society of America, was set up in 1955. The purpose of this committee is to study the soil compaction problem and to gather information to help guide the progress of understanding and solving the soil compaction problem. Three subcommittees from each group have been appointed, one to define terms involved in soil compaction, one to review the present knowledge of the subject, and one to study methods and instrumentation for making measurements involved in soil compaction studies.

The Subcommittee on Terminology classified the types of compacted soils as induced pans and genetic pans. Induced pans are those which are caused by applications of surface pressure to the soil (pressure pans), or caused by filtering of fine particles to form a dense layer (filter pans). Genetic pans are those dense layers of soil which occur naturally. The following classifications and definitions of soil conditions have been proposed for reporting research on soil compaction:

Type I. Induced Pans

A. Pressure pans are horizontal layers having a higher bulk density and lower total porosity than the soil material directly above and below. The top of the pressure pan usually coincides with the lower depth of normal cultivation and is never more than 12 inches from the surface of the soil. The mechanical analysis and chemical properties of the pressure pan layer is similar to that of the soil immediately above and below the pan. In cultivated fields the pressure pan may be more pronounced in traffic row middles than it is immediately under the crop row. Pressure pans are most common in medium-textured soils of low structural stability and in regions where the soil is not subject to frequent freezing and thawing when moist.

B. Filter pans are closely related to pressure pans, possibly being caused by collection of fine particles from the surface cultivated layers washing down and collecting in a pressure pan. They have all the characteristics of pressure pans, plus having coatings of fine particles (silt and clay) on the surfaces of the structural aggregates near the top of the pan.

For the purpose of this thesis these are the two definitions of interest. The subcommittee also described the following genetic pans: (a) claypans, (b) fragipans or siltpans, (c) indurated hardpans, (d) alkali pans, and (e) dense C or D horizons.

## Scope of This Thesis

This thesis deals with one small segment of the compaction problem, that of measuring the pressure distribution in soil caused by traffic over the land such as tractor, truck and implement tires, and tillage tools. If the pressures in the soil could be measured it would help to evaluate the forces causing soil compaction.

The contents of the thesis include a description of the development of a small (2-inch diameter by 3/4 inch thick) electrical resistance strain gage pressure cell (transducer); the characteristics of this cell and other soil pressure cells; a description of some auxiliary instrumentation used with cells; some experiences with rubber pressure pickups and a liquid pressure transducer; some results of the measurement of pressures at various depths under the rear tires of a tractor; and a theoretical discussion of pressure distribution in soil based on calculations by Froehlich's formula (5).

# REVIEW OF LITERATURE

## Soil Pressure Cells

The U. S. Waterways Experiment Station report (36) gives a complete description of most types of soil pressure cells developed for soil mechanics studies, such as measurement of the pressures in the soil under walls, footings, and tunnels. In addition, the report describes four series of tests performed at the Experiment Station with their newly developed pressure cell known as the WES cell. Their tests were planned to evaluate: (a) the effect of projection of the pressure cell from the surface of a rigid wall in terms of the indicated pressure of a sand mass bearing on the wall; (b) the effect of the compressibility of the cell mounted flush with the rigid wall in terms of the indicated pressure of the sand on the wall; (c) the effect of the relative dimensions of the cell on pressure indicated by a cell wholly within the sand mass; and (d) the effect of the cell compressibility on its ability to indicate pressure within the sand mass.

They found that if the ratio of cell diameter to its projection from a rigid surface exceeds 30, the pressure indicated is nearly the same as that indicated by the cell mounted flush with the surface. They determined that a pressure cell with a diameter-thickness ratio greater than 5, when placed near the center of a sand mass in a pressure chamber, indicated nearly the same pressure relative to the pressure applied at the surface of the sand. Their data showed that for values of the ratio of cell diameter to deflection (compression) exceeding 2000, there was very little change in indicated pressure. The exact relationship between the pressures indicated by the cells and those existing in the absence of cells was not established. However, they considered it very probable that the criteria established for cells mounted in a rigid wall, diameter-projection ratio greater than 30 and diameter-deflection ratio greater than 1000, do limit the range within which the cells indicate approximately the pressures which act on the wall in their absence.

Although the requirements for cells to measure pressures in soils under tillage implements and other agricultural traffic are somewhat different from those to measure soil pressures under walls, footings, and tunnels, there is enough similarity in the fundamental considerations to justify a brief description of some of the latter type of cells in this thesis. For a complete description of the Goldbeck cell, Carlson stress meter, WES soil pressure cell, California State Highway Department pressure cell, carbon pile cell, and acoustic stress meter, one should refer to the original publication or the Waterways Experiment Station report (36).

## Goldbeck Pressure Cell

As early as 1916 Goldbeck (6, 7, 8, 31) developed a cell which could be placed in soils to measure pressure through earth fills. It consisted of a cylindrical metal case with one end open. A movable metal piston was fitted loosely in the open end of the case and was held flush with the rim of the case by a thin metal diaphragm. Electrical contact was made between the movable piston and an insulated electrical contact button which was fastened inside the case. A small pipe, about 1/8-inch inside diameter, was fastened to the inside of the cell and extended to the ground surface. A single-conductor insulated wire connected with the contact button was carried to the surface with the pipe. Pressure acting on the movable piston maintained it in electrical contact with the bottom. Air pressure was applied through the pipe. The opening of the electric circuit, as shown by a lamp or ammeter, indicated an air pressure equal to the applied soil pressure. The cell dimensions varied, but were usually 5 1/2 inches in diameter and 1 1/2 inch thickness between the parallel faces.

## Carlson Stress Meter

The Carlson stress meter (2) is an adaptation of a strain meter to measure the stresses in concrete. This stress meter has been used successfully for the measurement of soil pressures against rigid walls and in special mountings within earth structures. The cell operates by transmission of pressure, which acts on a flat, circular face plate, through a confined liquid to a metal diaphragm whose deflection actuates a strain meter. The face plate and a thick back plate are welded together at their perimeter so that a thin chamber is left between them. The edges of both plates are made sufficiently thin to be flexible. A central diaphragm is formed by boring the back plate. The strain meter is attached to the rear of the base plate; the fixed arm and case being attached to the rigid portion of the plate, the movable arc being attached to the center of the diaphragm. The thin space between the face and back plate is filled with mercury. Pressure acting on the face plate is transmitted through the confined mercury to the diaphragm, which is deflected proportionately. Two electric resistance wires are coiled between insulators on the movable and fixed arms of the strain meter in such a manner that as strain is applied between the arms, tension is increased in one coil and diminished in the other. The electric resistance of the coils changes with the tension in the wire and these changes being opposite in the two coils, the effect is doubled. Deflection of the diaphragm in the stress meter by the applied pressure produces a resistance change in the strain meter.

This change in resistance is a simple function of the applied pressure. Although the soil pressures are successfully measured when the cell is mounted flush in walls, there is some question of the effect of the projecting strain meter on stress distribution within the soil mass. The face of the cell is approximately 7 inches in diameter and the strain meter, 1 inch in diameter, projects approximately 4 inches.

WES Soil Pressure Cell

The Waterways Experiment Station pressure cell (36) consists of a circular face plate welded at its perimeter to a thicker base plate. The face plate has a peripheral slot which forms a flexible joint between the two plates. A diaphragm is formed in the base plate by boring. The gage chamber thus formed is closed by a cover plate. A connector cable enters the gage chamber through a packing gland in the side of the base plate. The thin disc chamber between the face and base plates is filled with oil (recently, modified cells are filled with mercury). Pressure applied to the face plate is averaged and transmitted by the oil to the diaphragm. The radial strain produced in the diaphragm by the pressure is measured by an SR-4 electric resistance strain gage. An inactive or "dummy" strain gage mounted in the gage chamber on a piece of unstressed metal provides temperature compensation. Alteration in the active gage resistance produced by the diaphragm strain and indirectly by the applied pressure is amplified and indicated. A linear relation between applied pressure and resistance change can be attained. The WES cells range in size from three to 12 inches in diameter and from 1/2 to 1 1/4 inches in thickness.

California State Highway Department Pressure Cell

This cell was developed by the California State Highway Department (36) principally for the purpose of measuring subgrade pressures produced by wheel loads on pavements. An outer diaphragm, attached rigidly at its circumference to the body of the cell, forms the outer end of a thin, cylindrical oil chamber. Pressure applied to the outer diaphragm is transmitted by the oil to a smaller weighing diaphragm. An iron disc is held against the weighing diaphragm by a flat spring, and is separated from the poles of the U-shaped iron core of an electromagnet by a small air space. Deflection of the weighing diaphragm decreases the air gap between the disc and poles of the electromagnet. A rigid ring limits the travel of the disc and prevents damage by excessive pressures. Movement of the metal disc changes the magnetic flux in the gap and thus changes the reluctance of the circuit. A balancing unit consisting of a similar coil and gap is located separately from the cell in such a way as to be unaffected by the load on the cell. The cell and balancing unit are connected in a bridge circuit. The unbalance due to pressure applied to the cell causes an increase in current through the control arm of the bridge. The current change is a measure of the change in applied pressure. This cell is approximately seven inches in diameter and 1 5/8 inches in height.

## Carbon Pile Cells

Carbon pile cells are perhaps the earliest type of soil pressure cell. In spite of many attempts to employ the carbon pile as a practical measuring unit in soil pressure cells, there has been no success. The measuring element of the cell consists of a stack of thin carbon discs (17) mounted between metal plates. When pressure is applied to the ends of the stack, its electrical resistance decreases. The change is of sufficient magnitude to be measured with a bridge. The principal difficulty with the stacks appears to be that they do not retain calibration. However, in the laboratory where it is possible to recalibrate the stack frequently, good results have been obtained for dynamic tests and for short-duration static tests.

## Acoustic Stress Meter

The basic principle of this instrument (15, 19) is the dependence of the natural frequency of a freely vibrating string on the tension applied to it. Fundamentally, the cell consists of a face plate free to move relative to the cell housing, and acting through a hemispherical contact at the midpoint of a steel beam supported by a knife-edge bearing near each end. A piece of steel wire is stretched between rigid arms which extend from the tension side of the beam. External pressure applied to the face plate bends the beam and increases the tension in the wire proportionately. The wire is set in vibration by means of a small coil through which an electric current is switched momentarily. The vibration of the wire is then picked up and transmitted by the same coil and connector wires to an indicating device (head phone or cathode ray oscillograph, for example). Since the wire is vibrating freely, its frequency will be the natural frequency which results from the altered tension in the wire. This frequency is matched, either by direct comparison or by superposition, with that of an adjustable standard wire. The standard wire consists of a similar taut wire with calibrated, adjustable tension. This wire is actuated and its vibrations detected by a coil similar to the one in the cell. The tension in the standard wire is adjusted so that its tone matches that of the cell, or so that the superposed signals from both vibrating wires do not interfere or beat. The tension in the standard wire then corresponds to a particular pressure on the cell, as established by an initial calibration.

Soehne (33) evidently used some type of pressure cell in the soil for he made the following statement in his articles (as translated).

> Measurement of pressure in the soil is not completely simple. A compression pressure cell, in order to make exact measurements, must be just as hard as the surrounding soil or infinitely thin. But it is either harder than the surrounding soil, which loads to a concentration of the force-lines toward the pressure cell or it is softer which results in an envelopment of the pressure cell by the lines of force. Moreover, on introduction of the pressure cell into the soil, the original stratification density is disturbed to some extent. For this reason it is not easy to ascertain by measurement what pressure distribution is present on the load surface. On the other hand, however, an error of 25 percent in measuring the pressure or in calculating results only introduces a maximum compaction error of one percent pore volume. An exactness of 25 percent ought, however, to have been obtained in the determination of the pressure stress.

## Methods of Measuring Soil Deformation

### Plaster Cast and Glass Fronted Box

Nichols and Randolph in 1925 (21) developed the plaster cast method of studying soil stresses. The soil was stratified into layers by means of aluminum leaf or other delicate material and a definite pressure was applied. The soil was then removed one layer at a time and a cast made of the distorted surfaces of the aluminum leaf. A camera lucida was used for transferring the contours to coordinate paper for study. In another visual method Nichols (20) placed layers of soil and thin aluminum foil in a glass fronted box. Known forces were then applied to the surface of the soil by implements of various shapes, and the distortion of the aluminum leaf was noted. The pressure at the bottom of the soil in the box was measured with a Goldbeck gage. Later Kummer (13) with the same glass front box, coated the glass with levigated alumina and noted the scratches caused by the movement of the soil as a force was applied to the surface. Reaves and Nichols (25), with this method, photographed these scratches in the alumina to study the soil stresses.

## Bead Displacement

McKibben and Green (18) arranged small beads in the soil according to a predetermined color pattern. The beads were placed accurately at known distances vertically and horizontally. Wheels were then run over the soil containing the beads. The beads were dug up, and their displacement was taken to indicate the displacement of soil. From the displacements the deformation pattern was determined for steel wheels and for pneumatic tires.

## Plaster of Paris and Cement Bands

Soehne (33) placed bands of a mixture of plaster of paris and cement perpendicular to the direction of travel and at various depths to measure soil deformation under tractor and trailer tires. To place the mixture he drove a tube filled with plaster of paris and cement in the soil horizontally from a pit, and pushed the mixture out with a plunger as he pulled out the tube. After the tire had passed over the treated area he carefully excavated to determine the soil deformation.

## Bulk Density

By measuring the bulk density of a soil before and after loading, the amount of soil deformation caused by the load can be determined. A number (10, 11, 16, 38, 39) of workers have used core samples for determining bulk density.

The air pressure pycnometer (12, 22, 23, 29) can be used to determine the bulk density of the soil indirectly by determining the pore space volume of the soil. This instrument applies the principle of Boyle's law to a sample in a closed system, and permits the direct determination of the volume of the gaseous constituents by measurement of pressure-volume relationships at a constant temperature.

Vomocil (37) recently reported a gamma-ray absorption technique for the measurement of soil bulk density. This instrument should aid greatly in the research of determining the extent of compaction due to various loads.

Penetrometers

Several penetrometers (1, 26, 28, 35) have been developed to locate compacted layers and indicate the degree of compaction.

# APPARATUS

## Type A Soil Pressure Cell

Three different models were designed, built and tested during the development of the type A strain gage pressure cell. The first model consisted of a small brass box (2 inches in diameter and 0.7 of an inch in height) with a thin metal disc diaphragm held in place by a threaded ring top (Figure 1). At the center of the lower side of the metal disc was cemented a 1/2-inch SR-4 electrical resistance strain gage (type A-5, 120$\Omega$, gage factor 2) which was the active gage of the circuit (Figure 2). Another SR-4 strain gage was cemented to the bottom of the cell box for temperature compensation. This pressure cell operated satisfactorily, but had the disadvantage that its calibration was not linear (Figure 3, curve 1).

To overcome this difficulty of non-linear calibration, three new cells were constructed. The cell box construction was like those shown in Figure 4, but the strain gage arrangement was different. These cells had a 1/16-inch SR-4 strain gage (Type A-19, 60$\Omega$, gage factor 1/68) cemented at the center of the metal disc, and a gage from the same lot cemented to the bottom of the brass box for temperature

Fig. 1. First model of the type A strain gage pressure cell.

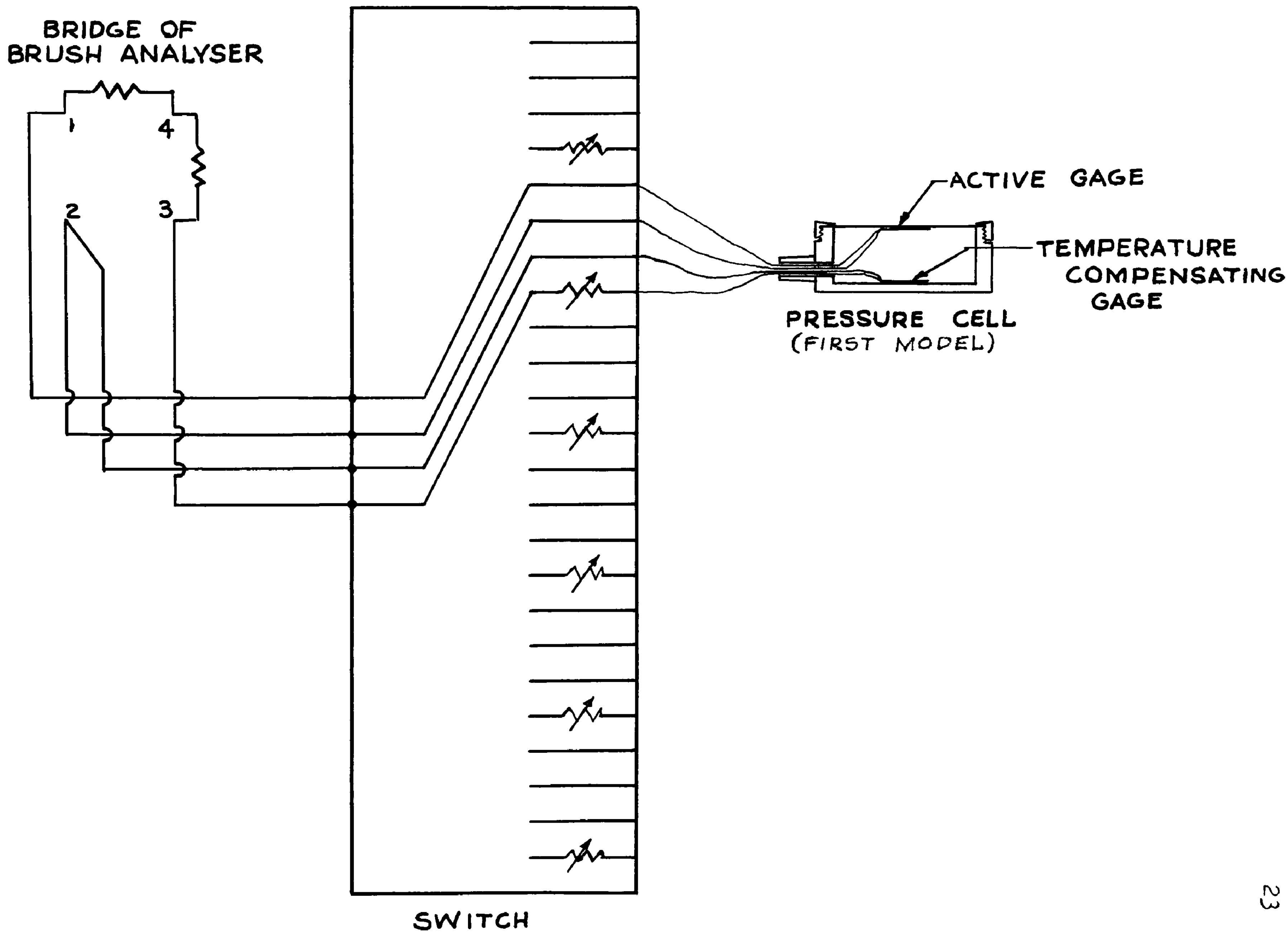


FIG. 2. DIAGRAM OF MULTIPLE SWITCH AND TYPE A CELL

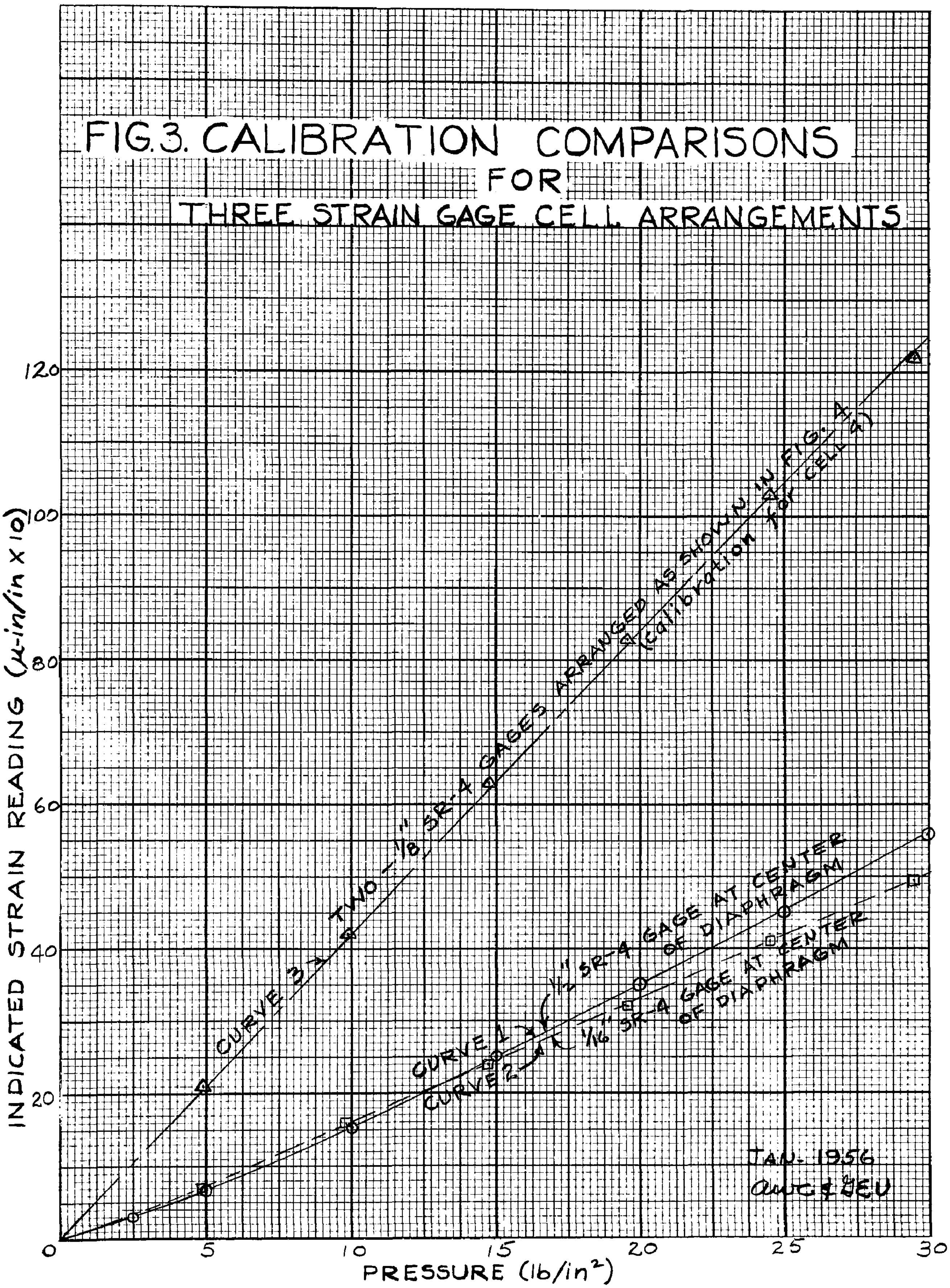
FIG.3. CALIBRATION COMPARISONS
FOR
THREE STRAIN GAGE CELL ARRANGEMENTS
INDICATED STRAIN READING (μ-in/in x 10)
PRESSURE (lb/in²)
CURVE 3 → TWO - 1/8" SR-4 GAGES ARRANGED AS SHOWN IN FIG. 4
(calibration for CELL 4)
CURVE 1 → 1/2" SR-4 GAGE AT CENTER OF DIAPHRAGM
CURVE 2 → 1/16" SR-4 GAGE AT CENTER OF DIAPHRAGM
JAN. 1956
AWC & JEU
0
5
10
15
20
25
30
20
40
60
80
100
120

compensation. This arrangement gave a straight line calibration between 2 1/2 and 30 psi but curved slightly from 0 to 2 1/2 psi (Figure 3, curve 2). There were two serious objections to this arrangement. First, the cell was hard to assemble with the temperature compensating gage on the bottom plate. Second, this gage indicated a slight strain in the bottom cover plate when calibrated in water. This strain did not cause an error when the cell was suspended in soil, because pressure was applied to both top and bottom as in the water calibration. However, it caused a significant error when the cell was placed in the bottom of a soil box, because then the bottom plate of the cell was not strained as it was in the water calibration. This caused the cell to read high. Another minor difficulty was that the direct inking oscillograph used was equipped with a calibration resistor for 120-ohm gages, the resistance of most of the gages used in the Agricultural Engineering Laboratories. This necessitated a different calibration setting from normal or changing of calibrating resistor.

Due to these difficulties the third model of the type A strain gage pressure cell was developed. A detailed sketch of this model is shown in Figure 4, and a sample calibration (curve 3) is shown in Figure 3. This cell has twice the sensitivity of the two previous models because of its two active gages. Twelve of these latest model cells were built

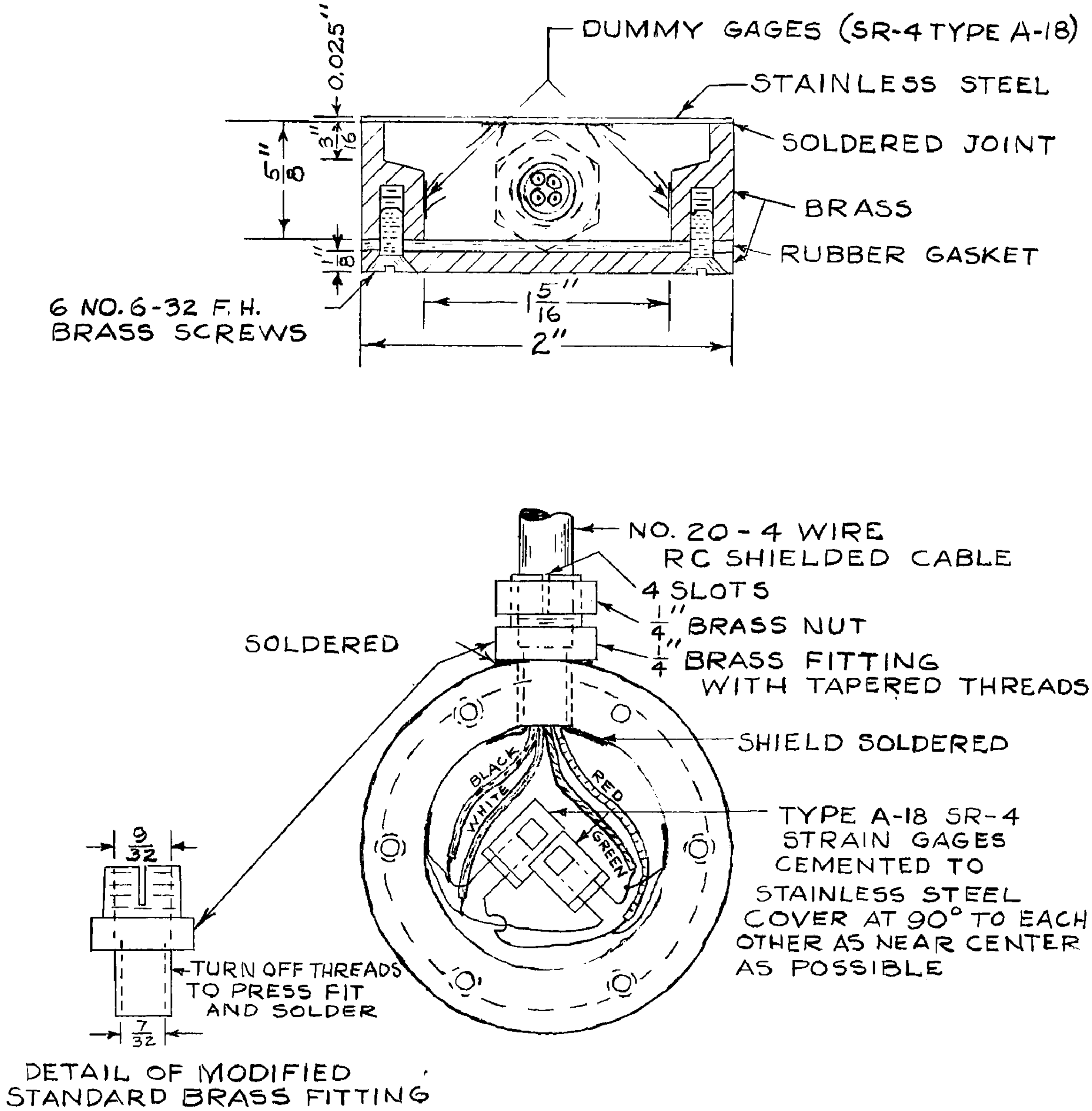


FIG. 4
TYPE A SOIL PRESSURE CELL

SCALE-ACTUAL SIZE

AUGUST 1955
awc & GEV

for use at the Powerama Plowing Demonstration held in Chicago, Illinois, in September 1955. Before the tests in Chicago the cells were calibrated from 0 to 30 psi. The calibrations in this region were linear. After these tests some of the chart readings indicated pressure measurements above 30 psi, so the cells were calibrated up to 60 psi. Above 40 psi the calibrations started to curve slightly so two of the cells were calibrated up to 90 psi to determine the characteristic of the cells in this region (Figure 5).

For future construction of cells it is suggested that the two "dummy" gages shown in Figure 4 be moved to opposite edges of the underside of the stainless steel disc. The length of the strain gages should be placed so that they indicate the radial stresses. This arrangement would make all four gages active. The two center gages should be in opposite arms of the Wheatstone bridge and the two outside gages should be in the other opposite arms.

The reason for this arrangement can be seen by examining Figure 24. The center gages would be in tension and the edge gages would be in compression.

## Equipment Used for Calibrating the Type A Pressure Cell

The first equipment used to calibrate the type A pressure cells consisted of a 5-quart pressure cooker for a

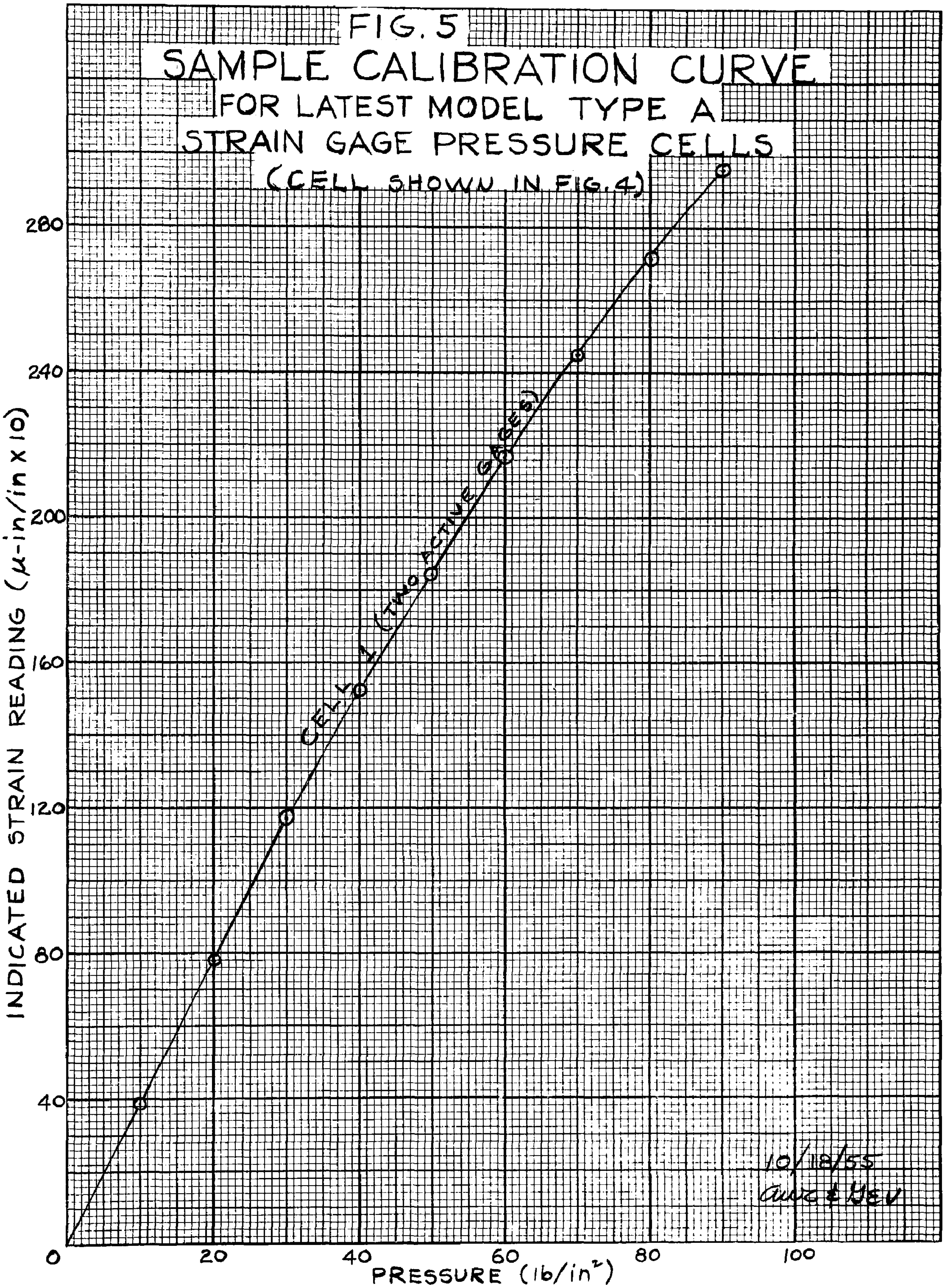
FIG. 5
SAMPLE CALIBRATION CURVE
FOR LATEST MODEL TYPE A
STRAIN GAGE PRESSURE CELLS
(CELL SHOWN IN FIG. 4)
CELL 1 (TWO ACTIVE GAGES)
INDICATED STRAIN READING (μ-in/in x 10)
PRESSURE (lb/in²)
0
20
40
60
80
100
40
80
120
160
200
240
280
10/18/55
AWC & GEV

pressure chamber, an air compressor to supply air under pressure, two control valves to regulate the air pressure accurately, and a mercury manometer to measure the air pressure in the chamber. The cells were placed in the chamber, which was filled approximately half full of water to reduce temperature fluctuations due to the compressed air. The top was then placed on the cooker and the leads were brought out the top through a rubber stopper to the amplifier and recorder. The air pressure above the water in the chamber was increased by 5 psi increments, and the resulting strain on the pressure cell measured and recorded.

The second set of calibration equipment consisted of a heavy steel tank with a special top and a mercury manometer. In this arrangement city water pressure was used to supply increments of pressure. The resulting strain was read and recorded. The top of the tank had a four-inch pipe plug which could be removed to put in the cells. The leads of the cells could be brought out through four rubber stoppers in the top of the tank. By this arrangement four cells could be calibrated at the same time. Later a calibrated 0-100 psi Bourdon-tube pressure gage was used to indicate the pressure instead of the mercury manometer.

## Soil Science Load Cell*

Figure 6 shows the construction of the load cells borrowed from the Soil Science Department of Michigan State University. A sample calibration curve for one of the cells is given in Figure 7.

## Liquid-Filled Rubber Pickups and a Liquid-Pressure Transducer

A small amount of work was done with liquid-filled rubber tubing and balloons connected to a pressure transducer. A Statham model No. P6-306-120 unbonded strain gage pressure transducer was used (Figure 8). It had a maximum input voltage of 7, resistance of 125.5 ohms and a calibration factor of 84.14. The manufacturer's calibration was checked with a dead weight tester and found to be accurate.

Red rubber and latex tubing and a balloon were used for pressure-pickup bulbs. These were calibrated with water pressure in the same manner as were the type A cells. As seen from the calibration data (Table I, and Figure 9), the balloon gave a linear calibration but the rubber tubing calibrations varied from a straight line due to the rigidity of the tubing walls.

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*The load cells were loaned to this project by A. E. Erickson, Soil Science Department, Michigan State University. They were designed and built by P. J. DeKoning, Applied Mechanics Department, Michigan State University, to be used by N. A. Willits for his research which will be reported in detail in his Ph. D. thesis, Michigan State University, 1956.

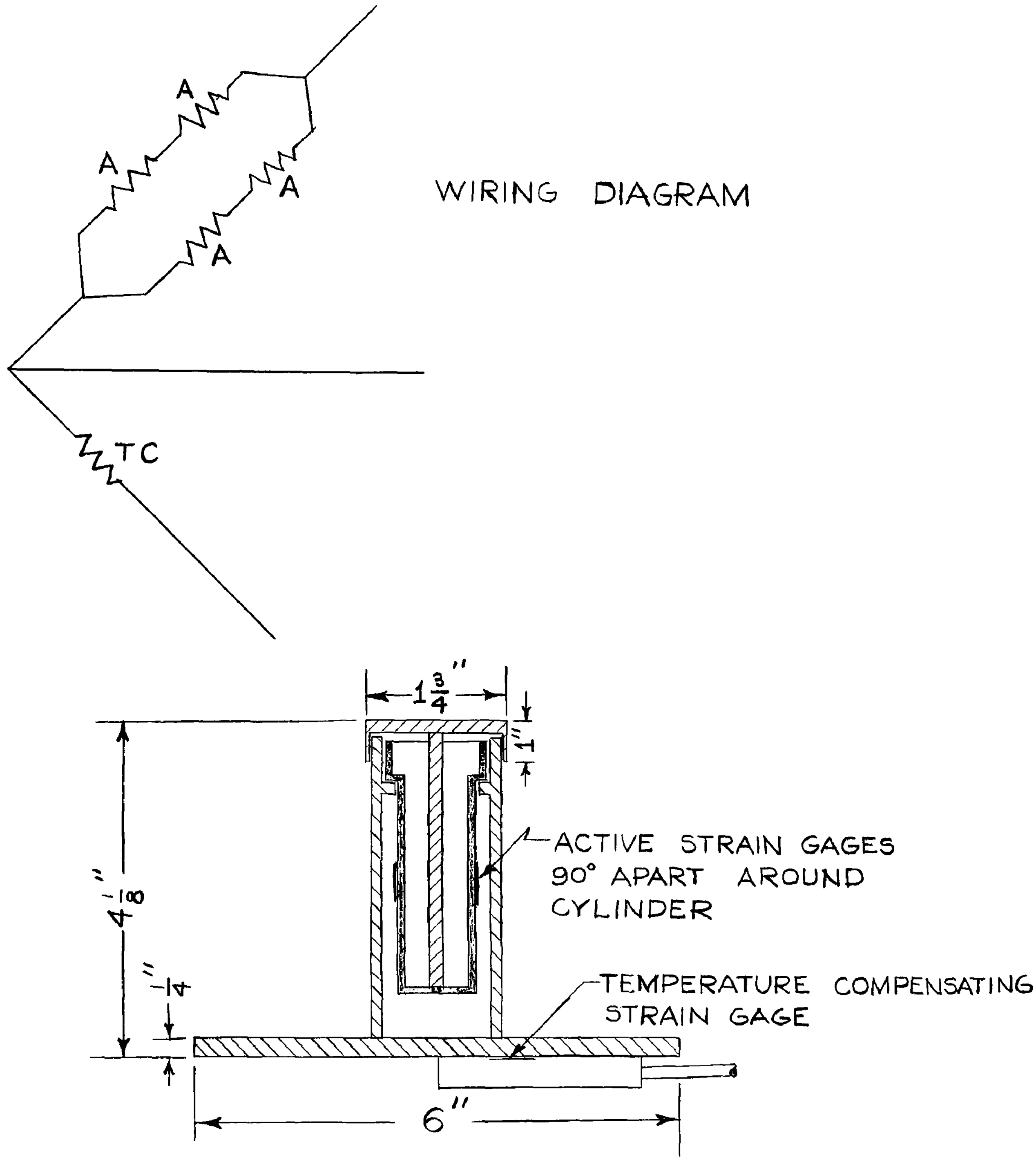



FIG. 6 SOIL SCIENCE LOAD CELL

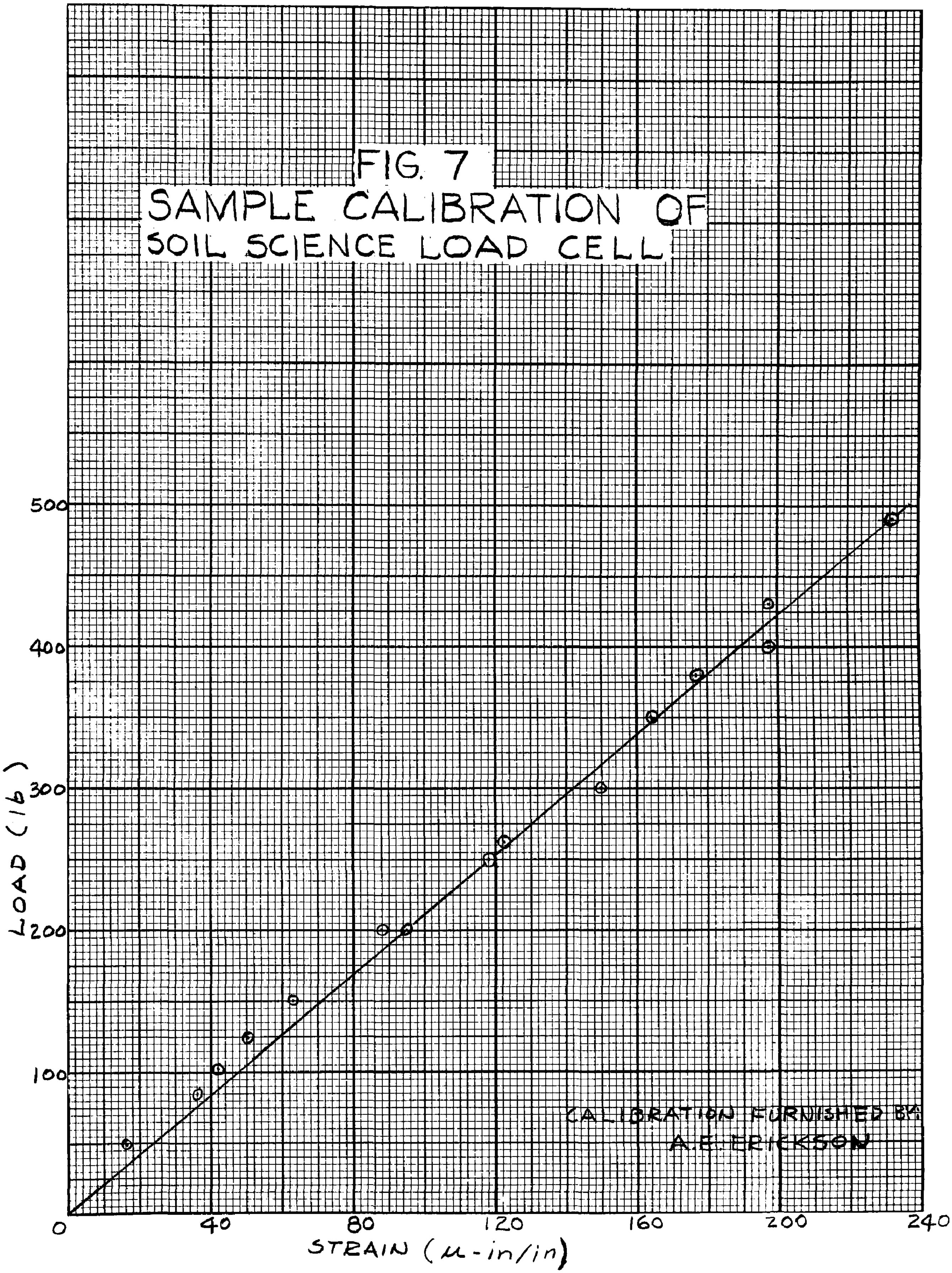
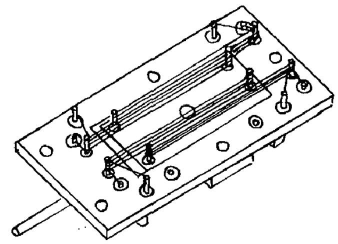


FIG. 7
SAMPLE CALIBRATION OF
SOIL SCIENCE LOAD CELL
CALIBRATION FURNISHED BY
A.E. ERICKSON
LOAD (lb)
100
200
300
400
500
0
40
80
120
160
200
240
STRAIN (μ-in/in)



THE STATHAM TRANSDUCER ELEMENT

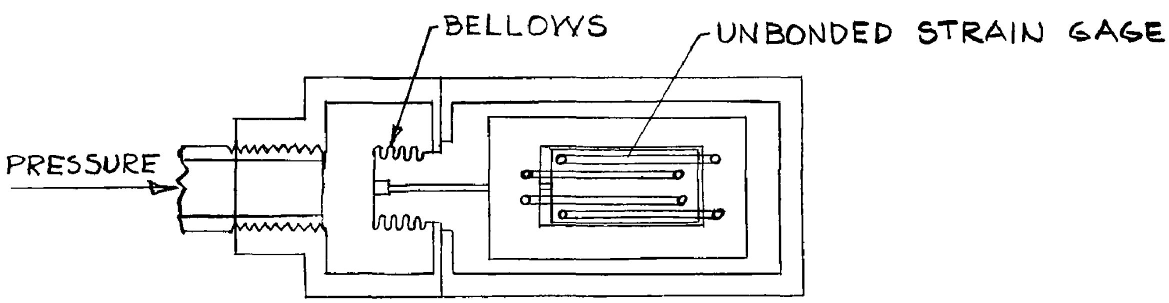



FIG. 8 STATHAM TRANSDUCER

TABLE I

WATER CALIBRATION OF RUBBER TUBING AND BALLOON PRESSURE PICKUPS WITH STATHAM TRANSDUCER[1]

| Water Pressure | | TUBING | | | | |
|---|---|---|---|---|---|---|
| | | Red Rubber 1/2" length | Red Rubber 1" length | Plastic 4" length | Latex 2" length | Balloon |
| in. Hg. | $lb/in^2$ | $\mu$ in/in x 10 | $\mu$ in/in x 10 | $\mu$ in/in x 10 | $\mu$ in/in x 10 | $\mu$ in/in x 10 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 4.91 | 47 | 50 | 36 | 36 | 82 |
| 20 | 9.82 | 101 | 106 | 81 | 94 | 164 |
| 30 | 14.72 | 156 | 167 | 130 | 155 | 246 |
| 40 | 19.61 | 214 | 222 | 183 | 227 | 328 |
| 50 | 24.53 | 273 | 285 | 239 | 306 | 410 |

[1] Tubing and connectors filled with instrument oil. Readings are indicated strain in transducer. Measurements made with Young Indicator.

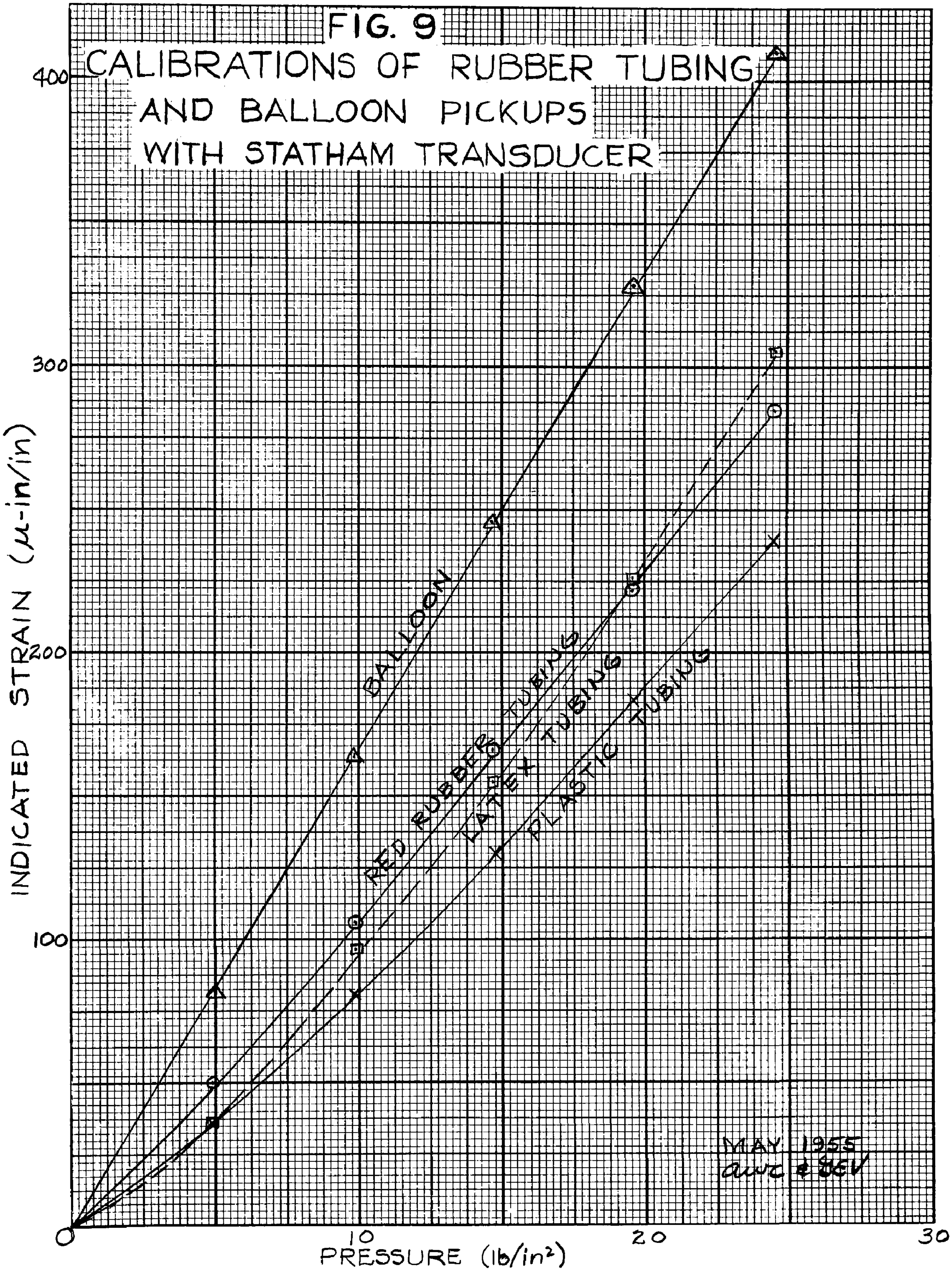


FIG. 9
CALIBRATIONS OF RUBBER TUBING AND BALLOON PICKUPS WITH STATHAM TRANSDUCER
BALLOON
RED RUBBER TUBING
LATEX TUBING
PLASTIC TUBING
INDICATED STRAIN (μ-in/in)
PRESSURE (lb/in²)
0
10
20
30
100
200
300
400
MAY 1955
awc & SEV

## Amplification and Recording Equipment

For the laboratory work a Brush amplifier (type BL320) and dual-channel recorder (type BL202) amplified and recorded the change in voltage signal due to the change in resistance of the strain gages when pressure was applied to the cells. For part of this work and when the liquid transducer was used, the signal was picked up with a Young Strain Indicator.

The measurements taken at the Powerama Plowing Demonstration were made with an Offner six-channel Dynagraph Recorder (Figure 10).

## Switching Mechanisms

To be able to read pressures at more than one point at a time with one amplifier and recorder, two selector switches were designed and built for the two-arm cells. The first model (Figure 11) was a six-channel selector consisting of a four-pole, 11-position rotary shorting-type switch, six 0-2 ohm resistors, and the necessary connectors for six cells and the amplifier. The two-ohm variable resistors were put in series with the temperature compensating gages of the pressure cell as shown in Figure 2. In balancing the group of cells the first cell was balanced with the resistance and capacitance balances of the bridge amplifier. Then each additional cell was selected and enough resistance


Fig. 10. The Offner six-channel recording oscillograph.

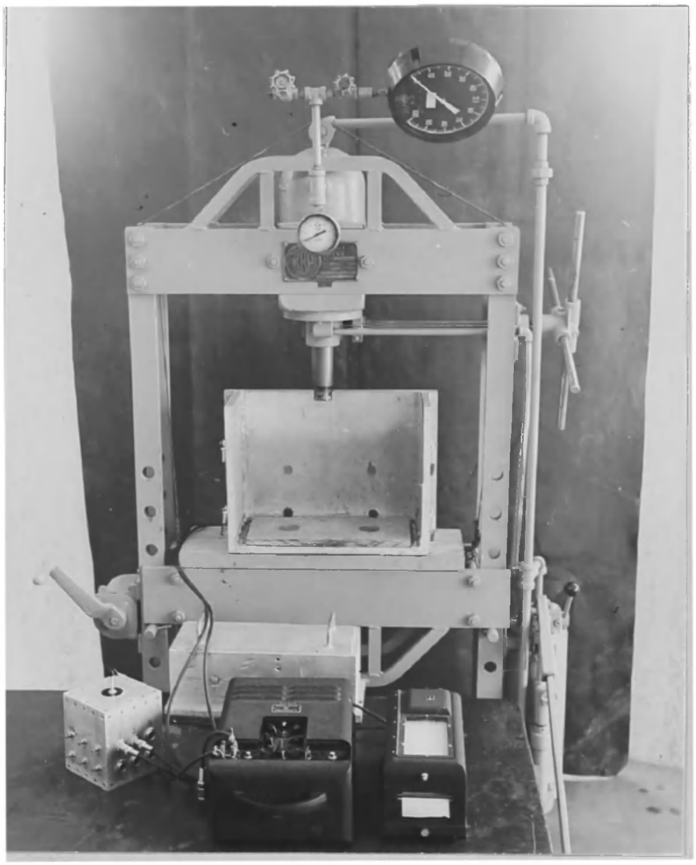


Fig. 11. General view of equipment for making soil pressure measurements in the laboratory.

added in series with the temperature compensating strain gage to balance it at the same position as the first cell.

Essentially the same circuit was used in the second switch box as the first. It had 12 channels instead of six and was equipped with an automatic rotary switch (Automatic Electric Company - type 45) four banks of which had gold-plated contact points. These four banks switched the strain gage leads. Two other banks which were not gold-plated connected indicator lights showing the cell connected to the amplifier and recorder.

## Soil Box

The soil box in which the cells were placed for testing and to measure the pressure in confined soil at various depths under various loads was 18 inches long, 8 1/3 inches wide, and 14 inches high (Figure 12). The plunger to apply pressure to the soil was designed to transmit a uniform load up to 100 pounds per square inch (Figure 11). It had an area of 142 square inches to fit the soil box which had a cross-sectional area of 144 square inches.

## Hydraulic Press

A K. R. Wilson hydraulic press (Model 37E, 50-ton capacity) applied the loads to the soil (Figure 11).

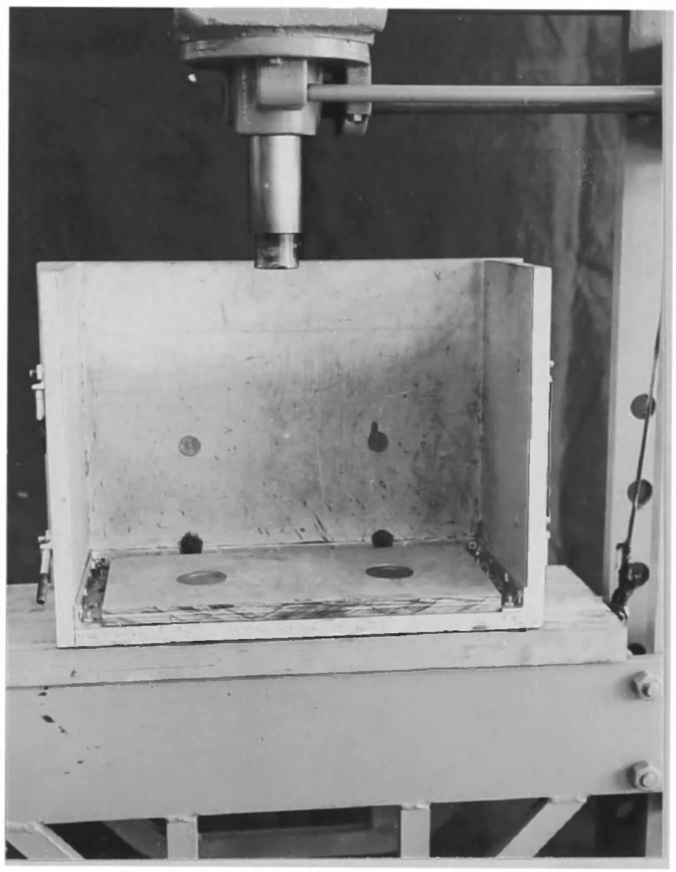


Fig. 12. Box for testing the pressure cells and pickups and for measuring pressure variations in soil with depth under various applied loads.

The hydraulic press was calibrated with a Bourdon tube pressure gage connected to the fluid chamber and a platform scale to measure applied load. The gage pressure was then plotted against applied load. This calibration was used to determine the loads applied to the soil. This method of measuring applied load is not recommended but seemed to give satisfactory results. A ring load cell attached to the plunger of the press would be more dependable.

# PROCEDURE

## Testing Type A Cells in Soil Box

To determine how the type A cells would function in soil three series of measurements were made. First, three cells were placed in the bottom of the soil box with the tops of the cells flush with the top of a false bottom (Figure 15-a). Four inches of soil (Maumee sandy loam) were placed in the box and leveled with a template. Loads of two to 12 pounds per square inch were applied to the surface of the soil in two pound-per-square-inch increments, and the resulting pressures on the cells were measured. Since the tops of the cells were flush with the top of the false bottom, the soil pressure on both of these was assumed to be the same. The soil was then removed and a new batch placed in the box for the next test. This procedure was repeated three times, giving nine measurements for each pressure applied.

The cells were then suspended in an eight-inch depth of soil with four inches of soil above the top of the cell (Figure 15-b). As in the first series of tests the soil was placed loosely in the box and leveled with a template. Pressure was applied in the same manner and amount as in the first series of tests and the same number of replications was made.

Then the cells were placed on the bottom of the box and soil was placed in the box in the same manner as in the first two series of tests with four inches of soil above the tops of the cells (Figure 15-c). Pressures were applied and measured in the same manner and number as before.

### Testing the Soil Science Load Cell in Soil Box

Two of the type A cells and a load cell were suspended in loose Hillsdale sandy loam in the soil box. The tops of the cells were placed two inches below the surface of the soil (Figure 17-a). Pressures of two to 12 pounds per square inch were applied to the surface of the soil in two pound-per-square-inch increments. The pressure indicated by the cells for each applied load was measured with the Brush amplifier and recorder.

### Testing Liquid-Filled Pressure Pickups in Soil Box

A few soil pressure measurements were made in the soil box to test the rubber tubing and balloon pickups. In most cases the tubing or balloons were placed at the same depth in the soil as type A cells for comparative readings. The pickups were suspended in the soil and various loads were applied in the same manner as in the type A cell tests.

Measuring Change in Soil Pressure with Depth in the Soil Box

A series of soil pressure measurements were made with Hillsdale sandy loam at 12.9 percent moisture. Two type A cells were placed in the bottom of the soil box with the tops of the cells flush with a false bottom, as shown in Figure 12. The soil was placed in the box in two to 12-inch layers and leveled with a template. Loads of two to 12 pounds per square inch were applied to the surface of each depth of soil and the resulting pressure on the cells was measured. The depth of the soil was measured after each load was applied to determine the degree of compaction.

## Testing Cells at Powerama

The General Motors Corporation, to celebrate the production of their 100 millionth diesel horsepower, staged a gigantic Powerama Show. One part of the show was a plowing demonstration utilizing a diesel-powered tractor. Fourteen train-car loads of Maumee sandy loam soil were imported from South Bend, Indiana, and placed on asphalt paving adjacent to Soldier's Field in Chicago. The soil covered an area 286 feet long and 60 feet wide to a depth of approximately 15 inches in the 40-foot-wide plowed area.

The soil was scheduled to be plowed 13 times a day for 26 days. Actually due to rain and other interruptions, the soil was plowed approximately 286 times during the demonstrations, plus 30 times for practice, making a total of approximately 316 times.

An Oliver Super 99 GM diesel tractor pulled a six-bottom moldboard plow (16-inch bottoms). This 72 drawbar horsepower tractor with plow turned an eight-foot strip each pass. The center 40 feet of the plot was plowed in about five minutes with five troughs.

After the soil had been plowed, the moisture which was lost during plowing was replaced by a 500-gallon sprayer. After spraying the soil was compacted to its original bulk density with a 38-inch diameter sheep's foot tamper and the surface was smoothed with a pneumatic tired roller. The plot was ready for the next demonstration plowing.

During the plowing demonstration the Agricultural Engineering and Soil Science Departments of Michigan State University, and the U. S. Department of Agriculture cooperated in making pressure measurements in the soil and soil physical measurements.* The objectives were (a) to measure the pressures in the soil under the tires of the tractors

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*Only a small amount of the pressure data obtained is reported and discussed in this thesis, to show how the cells functioned. A complete analysis of the pressure data will be reported by G. E. VandenBerg of the Agricultural Engineering Department in a Michigan State University master's thesis. The soil physical measurement will be reported by A. E. Erickson of the Soil Science Department, Michigan State University.

and implements at various distances horizontally and vertically from the center of the tires, (b) to gain field experience in using the newly-developed type A strain gage pressure cells, (c) to compare soil pressure measurements made with two types of strain gage pressure cells, and (d) to measure the changes in the physical properties of the soil during the series of plowings.

To make the pressure readings six type A cells were buried at the same depth and 0.4 of a foot apart (Figure 13) on centers perpendicular to the direction of travel of the tractor. During the demonstration the cells were placed at various depths in order to obtain the change in soil pressure with depth under the tire loads.

To make a comparison of soil pressure measurements made with the type A cells and some load cells, furnished by the Soil Science Department, two of each of the cells were placed in line with the travel of the tractor (Figure 14). The tops of all four cells were placed at the same distance below the surface of the soil. As each tractor or equipment tire passed over the cells the pressure measurements were recorded. One of the load cells did not function properly, however, so a comparison was obtained between only one type A cell and one load cell.

Fig. 13. Method of placing type A cells in the soil at the plowing demonstration in Chicago.

Fig. 14. Method of placing type A cells and load cells in soil at the plowing demonstration in Chicago.

# RESULTS AND DISCUSSION

## Performance of the Type A Pressure Cell

The results of the tests of the type A cells in Maumee sandy loam are presented in Table II and Figure 15. Since the tops of the cells were flush with the top of the false bottom (Figure 15-a) in the first series of tests these pressure readings were considered as the base. Then the tests in which the cells were suspended in soil and those in which the cells were placed in the bottom of the box without a false bottom were compared with the above tests. Comparing curves 1 and 2 of Figure 15, it can be seen that there was no significant error due to suspending the cells in loose Maumee sandy loam soil. With a larger cell, according to Soehne (33) and the Waterways Experiment Station (36), this error is appreciable due to the fact that the cell is harder than the surrounding soil which causes loads to concentrate the force-lines toward the pressure cell giving a higher pressure reading than when the cell is flush with a surface. Curve 3, Figure 15, shows that in a loose soil with the cell on the bottom of the box an error of as much as 25 percent can be obtained. In this case the cells are not free to move with the soil as the

TABLE II

PRESSURE MEASURED WITH TOPS OF TYPE A CELLS FLUSH WITH THE TOP OF A FALSE BOTTOM, CELL SUSPENDED IN SOIL, AND CELLS RESTING ON BOTTOM OF SOIL BOX[1]

| Test No. | Cell No. | Pressure Applied (lb/in²) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 2 | 4 | 6 | 8 | 10 | 12 |
| | | lb/in² | lb/in² | lb/in² | lb/in² | lb/in² | lb/in² |
| | | Top of Cells Flush with Top of False Bottom | | | | | |
| 1 | 4 | 2.4 | 4.6 | 7.0 | 8.6 | 11.0 | 13.4 |
| | 8 | 2.4 | 4.0 | 5.9 | 7.8 | 10.5 | 12.4 |
| | 9 | 2.0 | 4.4 | 6.2 | 8.6 | 10.8 | 13.2 |
| 2 | 4 | 1.9 | 4.3 | 6.2 | 8.2 | 10.3 | 12.7 |
| | 8 | 1.7 | 4.0 | 5.9 | 8.1 | 10.2 | 12.6 |
| | 9 | 2.2 | 4.0 | 6.2 | 7.9 | 10.1 | 12.1 |
| 3 | 4 | 2.2 | 4.3 | 6.2 | 8.2 | 10.6 | 12.5 |
| | 8 | 1.7 | 3.8 | 5.5 | 7.8 | 9.5 | 11.9 |
| | 9 | 1.8 | 3.1 | 5.1 | 6.4 | 8.6 | 10.1 |
| Average | | 2.0 | 4.0 | 6.0 | 8.0 | 10.2 | 12.3 |
| | | Cells Suspended in Soil | | | | | |
| 4 | 4 | 2.2 | 4.1 | 6.2 | 8.4 | 10.8 | 13.0 |
| | 8 | 2.4 | 3.8 | 5.9 | 7.4 | 9.8 | 11.9 |
| | 9 | 1.8 | 4.0 | 5.7 | 7.9 | 10.1 | 12.6 |
| 5 | 4 | 1.7 | 3.8 | 5.8 | 7.7 | 9.8 | 12.0 |
| | 8 | 1.7 | 3.8 | 5.5 | 7.8 | 10.0 | 12.4 |
| | 9 | 2.4 | 4.2 | 6.4 | 8.4 | 10.6 | 12.8 |
| 6 | 4 | 1.9 | 4.1 | 6.0 | 8.2 | 10.1 | 12.2 |
| | 8 | 2.1 | 3.6 | 5.7 | 7.4 | 9.5 | 11.4 |
| | 9 | 1.8 | 3.7 | 5.5 | 7.5 | 9.2 | 11.7 |
| Average | | 2.0 | 3.9 | 5.9 | 7.9 | 10.0 | 12.2 |
| | | Cell on Bottom of Soil Box | | | | | |
| 7 | 4 | 2.4 | 4.8 | 7.2 | 9.8 | 12.5 | 15.1 |
| | 8 | 3.1 | 5.2 | 7.8 | 10.5 | 13.8 | 16.2 |
| | 9 | 2.4 | 5.1 | 7.5 | 10.4 | 13.0 | 15.6 |
| 8 | 4 | 2.6 | 5.3 | 7.7 | 10.3 | 13.2 | 15.9 |
| | 8 | 2.4 | 4.8 | 7.4 | 9.8 | 12.6 | 15.2 |
| | 9 | 2.2 | 4.6 | 6.8 | 9.5 | 11.9 | 14.5 |
| 9 | 4 | 2.9 | 5.5 | 8.2 | 10.8 | 13.5 | 16.3 |
| | 8 | 3.1 | 5.2 | 7.8 | 10.0 | 12.8 | 15.2 |
| | 9 | 2.0 | 4.6 | 6.6 | 9.2 | 11.4 | 14.1 |
| Average | | 2.5 | 5.0 | 7.4 | 10.0 | 12.7 | 15.3 |

[1]Maumee sandy loam - depth of soil above cell, 4 inches.

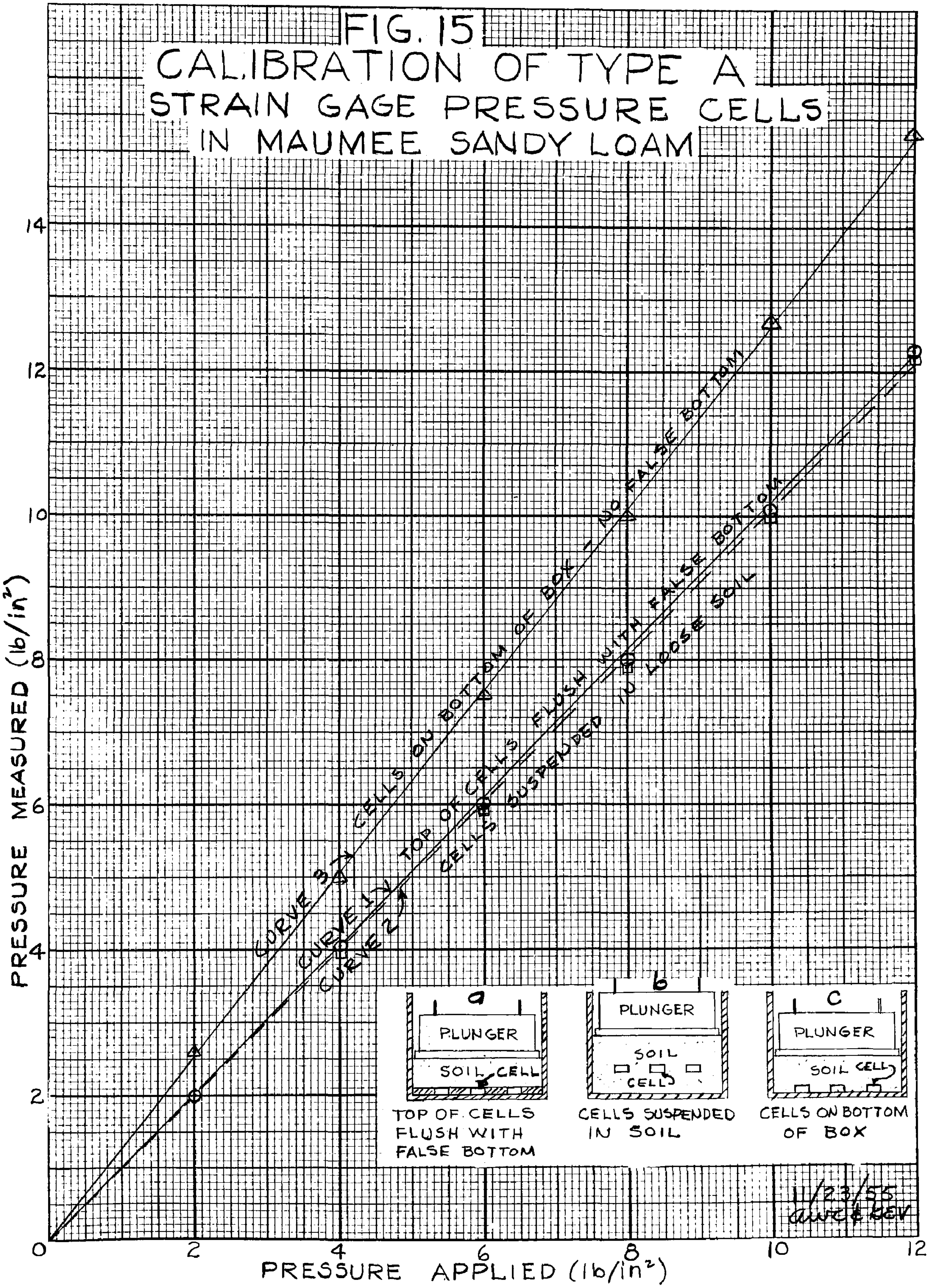


FIG. 15
CALIBRATION OF TYPE A
STRAIN GAGE PRESSURE CELLS
IN MAUMEE SANDY LOAM
PRESSURE MEASURED (lb/in²)
PRESSURE APPLIED (lb/in²)
0
2
4
6
8
10
12
14
CURVE 3 CELLS ON BOTTOM OF BOX - NO FALSE BOTTOM
CURVE 1 TOP OF CELLS FLUSH WITH FALSE BOTTOM
CURVE 2 CELLS SUSPENDED IN LOOSE SOIL
a
PLUNGER
SOIL
CELL
TOP OF CELLS FLUSH WITH FALSE BOTTOM
b
PLUNGER
SOIL
CELL
CELLS SUSPENDED IN SOIL
c
PLUNGER
SOIL
CELL
CELLS ON BOTTOM OF BOX
11/23/55

soil is compacted. The soil to the side of the cell compacts causing a concentration of load on top of the cells resulting in a higher pressure in the soil than would be present if the cells were not there. This error constitutes a maximum in that the bulk density of the soil was a minimum. If the bulk density of the soil is increased there is less compaction to the side of the cell and therefore less concentration of load on the cell.

## Comparative Pressure Measurements with the Bevelled Top and Flat Top Strain Gage Pressure Cells

There was some question as to whether the slight bevel on the top of the first model pressure cells (Figure 1) would affect the pressure measurements. In order to determine this the data in Table III was obtained. The first model cells were compared with the latest model cells (Figure 4) by placing them in the bottom of the soil box with their tops flush with the false bottom. As can be seen from the data there was no significant differences in the pressure measurements made with the two cells.

## Comparison of the Type A and Load Cells

In Figure 16 pressure measurements made with the type A cell are plotted against measurements made with the load cell

TABLE III

COMPARATIVE PRESSURE MEASUREMENTS WITH THE BEVELLED TOP AND FLAT TOP STRAIN GAGE PRESSURE CELLS

| Test No. | Pressure Applied ($lb/in^2$) | | | | | |
|---|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 10 | 12 |
| | $lb/in^2$ | $lb/in^2$ | $lb/in^2$ | $lb/in^2$ | $lb/in^2$ | $lb/in^2$ |
| | Bevelled Top Cell[1] | | | | | |
| 1 | 1.7 | 3.0 | 5.2 | 7.0 | 9.1 | 11.0 |
| 3 | 2.5 | 4.5 | 6.4 | 8.5 | 10.5 | 12.0 |
| 5 | 1.7 | 4.3 | 6.2 | 8.2 | 9.8 | 11.8 |
| Average | 2.0 | 3.9 | 5.9 | 7.9 | 9.8 | 11.6 |
| | Flat Top Cell 9 | | | | | |
| 2 | 1.8 | 3.5 | 5.7 | 7.5 | 9.2 | 11.4 |
| 4 | 2.0 | 3.7 | 5.7 | 7.5 | 9.7 | 11.7 |
| 6 | 2.0 | 4.0 | 5.7 | 7.7 | 9.5 | 11.4 |
| Average | 1.9 | 3.7 | 5.7 | 7.6 | 9.5 | 11.5 |

TABLE IV

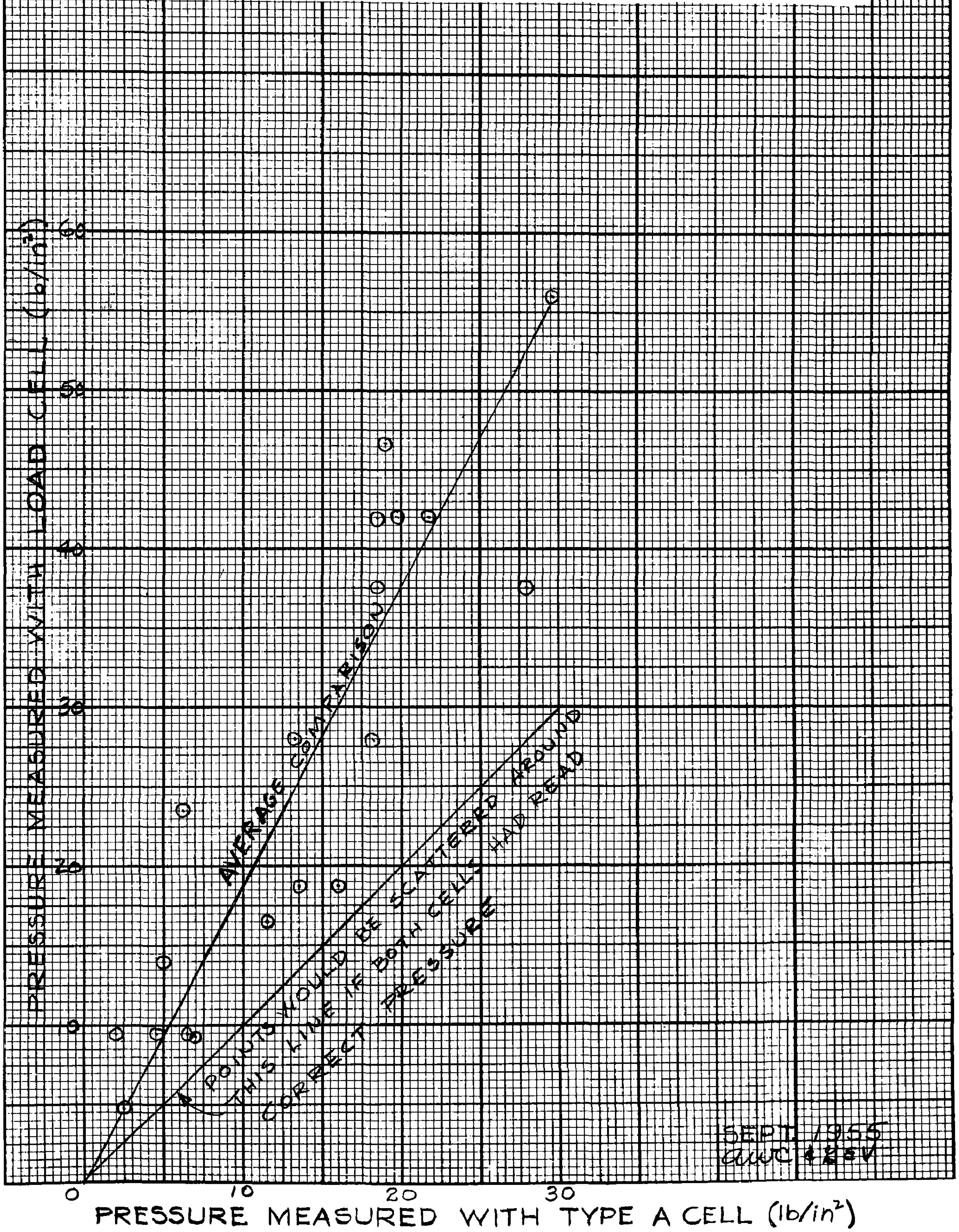
COMPARISON OF PRESSURE MEASUREMENTS IN MAUMEE SANDY LOAM SOIL* MADE WITH TYPE A AND LOAD CELLS

| Distance Below Soil Surface | Pressure Measured With Load Cell | Pressure Measured With Type A Cell | Load Applied With |
|---|---|---|---|
| in. | lb/in$^2$ | lb/in$^2$ | |
| 10 | 9.4 | 6.9 | Plow Tire |
| 3 | 37.5 | 28.1 | R. Trac. Tire (Plowing) |
| 10 | 42.0 | 18.4 | R. Trac. Tire (Spraying) |
| 10 | 37.5 | 18.4 | Sprayer Tire |
| 10 | 42.0 | 19.8 | R. Trac. Tire (Spraying) |
| 10 | 42.0 | 21.4 | Sprayer Tire |
| 10 | 18.7 | 16.0 | R. Trac. Tire (Tamping) |
| 10 | 9.4 | 4.4 | S. F. Tamper |
| 10 | 13.9 | 5.0 | F. Trac. Tire (Tamping) |
| 10 | 46.7 | 16.5 | R. Trac. Tire (Tamping) |
| 10 | 23.4 | 6.3 | R. Trac. Tire (Rolling) |
| 10 | 9.4 | 2.1 | Plow Tire |
| 1 | 56.1 | 29.7 | R. Trac. Tire (Plowing) |
| 10 | 4.7 | 2.5 | F. Trac. Tire (Plowing) |
| 10 | 16.3 | 11.6 | R. Trac. Tire (Plowing) |
| 10 | 18.7 | 13.5 | F. Trac. Tire (Spraying) |
| 10 | 28.0 | 17.2 | R. Trac. Tire (Spraying) |
| 10 | 9.4 | 6.6 | F. Trac. Tire (Rolling) |
| 10 | 28.0 | 13.2 | R. Trac. Tire (Rolling) |

*The mechanical analysis of the Maumee sandy loam was 66.4% sand, 28.2% silt, and 5.4% clay.

FIG. 16

COMPARISON OF PRESSURE MEASUREMENTS IN MAUMEE SANDY LOAM SOIL MADE WITH TYPE A AND LOAD CELLS



under various surface loadings. The tire or implement applying the load can be found in Table IV.

It is not surprising that the points of the curve are scattered because of the nature and position of the load. Even though the same tire or implement applied the load to both cells, the lugs were probably not in the same position above both cells especially in case of the rear tractor tire therefore one would expect the readings to vary. On close examination it can be seen that the pressures measured under the front tire of the tractor, and the plow and sprayer tires fall closer to the "average comparison" line than do the pressures measured under the rear tractor tires.

If both cells had indicated the true pressure in the soil where measurements were made they should have deviated from points along the 45-degree line in Figure 16. Because they deviated from points along a line above the 45-degree slope it must be concluded that either the load cell indicated a higher pressure than the true value or the type A cell indicated a lower pressure than the true value. From the analysis shown in Figure 15 the indicated pressure measurements made with type A cells should not be significantly low. Therefore from the data available it is assumed that the load cell indicated a pressure approximately twice as high as the true pressure in this Maumee sandy loam soil with a very high bulk density.

Figure 17 is a sketch of the position of the type A and load cells before and after pressure was applied to a loose Hillsdale sandy loam soil. A comparison of pressures measured in very loose Hillsdale sandy loam is given in Table V. This shows that in a very loose soil the indicated pressure of the load cell would be quite high. This test should be repeated several times before accepting these readings as the exact ratios of the indicated pressure to the true pressure for this bulk density. It is an indication, however, of the maximum error that might occur in using the load cells for measuring pressures in very loose soil.

There are two basic reasons for the load cell to indicate a pressure higher than the true pressure. First, the base has 26.3 square inches as compared to an area of the top of the cell of 2.4 square inches. This allows less settling of the cell with the soil which causes a concentration of load on the top of the cell. Second, the soil around the cell compacts and the cell does not compress appreciably causing a concentrated pressure on top of the cell which results in a high indicated pressure.

## Uses and Limitations of the Type A Pressure Cells

The type A pressure cell should give relatively accurate pressure measurements when it is placed within a homogeneous soil mass. When it is being used near a hardpan it should be placed so the top of the cell is flush with the top of the

TABLE V

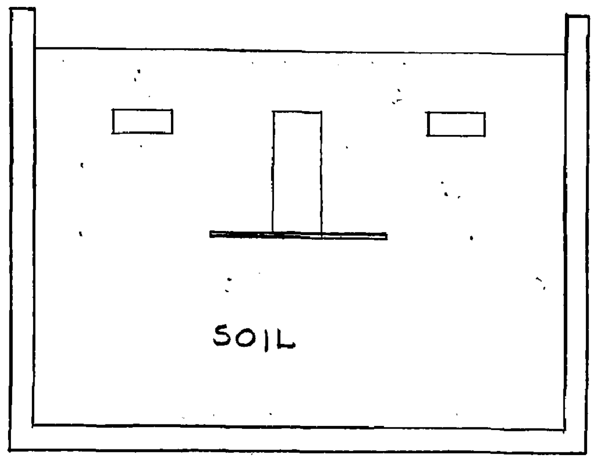
COMPARISON OF TYPE A AND LOAD CELLS IN VERY LOOSE HILLSDALE SANDY LOAM

| Pressure Applied | Pressure Measured (lb/in$^2$) | | | |
|---|---|---|---|---|
| | Type A | | | Load Cell |
| lb/in$^2$ | Cell 1 | Cell 2 | Average Cell 1 and 2 | |
| 2 | 1.8 | 2.3 | 2.0 | 2.2 |
| 4 | 3.8 | 3.8 | 3.8 | 13.0 |
| 6 | 5.8 | 5.7 | 5.8 | 43.3 |
| 8 | 7.7 | 7.3 | 7.5 | 95.5 |
| 10 | 10.0 | 9.5 | 9.8 | 186.6 |
| 12 | 11.6 | 10.7 | 11.2 | 243.0 |

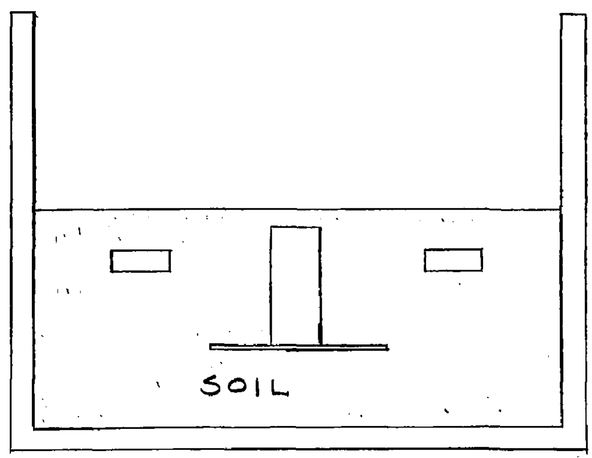
Height of load cell - 4.1 in.
Diameter of top of load cell - 1 3/4 in.
Diameter of bottom of load cell - 6 in.
Height of type A cells - 0.7 in.
Diameter of type A cells - 2 in.

Initial depth of soil:
Above all cells - 2 in.
Below type A cells 1 and 2 - 9.8 in.
Below load cell - 6.4 in.

Final depth of soil:
Above type A cell 1 and 2 - 1.3 in.
Above load cell - 0.6 in.
Below type A cell 1 and 2 - 5.3 in.
Below load cell - 2.6 in.




a. BEFORE PRESSURE WAS APPLIED




b. AFTER PRESSURE WAS APPLIED

FIG. 17 POSITION OF TYPE A AND LOAD CELLS BEFORE AND AFTER PRESSURE WAS APPLIED.

pan or placed within the pan with the soil above the cell compacted to its original bulk density.

This cell should give relatively reliable measurements in uncemented soil. It is probable that it would not give accurate results in cemented soils unless the cell is placed in the soil and then the soil given enough time to wet and dry sufficiently to cement around the cell.

## Performance of Rubber Pickups and Pressure Transducer in Soil

There were not enough measurements made with the rubber tubing pickups or the balloons to establish any definite conclusions. The indications, as shown in Table VI, are that the rubber tubing and balloon pickups read low at the higher pressures.

Since the indications were that it would take a considerable amount of development to devise a satisfactory liquid-filled pickup it was decided to concentrate on the strain gage pickups and postpone the work on the former. One definite disadvantage of the liquid-filled pickups was that it would be difficult to devise a piping system so that more than one bulb could be used with one pressure transducer.

TABLE VI

PERFORMANCE OF RUBBER PRESSURE PICKUPS USED WITH THE STATHAM TRANSDUCER

| Pressure Applied lb/in² | Pressure Measure (lb/in²) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | With Red Rubber Tubing | | | Balloon* | | | | |
| | Soil Depth (inches) | | | Test. No. | | | | |
| | 2 | 4 | 6 | 1 | 2 | 3 | 4 | Ave. |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1.8 | 1.8 | 2.0 | 1.7 | 1.6 | 1.6 | 1.9 | 1.7 |
| 4 | 3.8 | 3.8 | 4.1 | 3.2 | 2.4 | 2.9 | 3.5 | 3.0 |
| 6 | 5.5 | 5.5 | 5.8 | 4.4 | 4.2 | 4.1 | 5.0 | 4.4 |
| 8 | 7.0 | 6.8 | 7.2 | 5.8 | 5.6 | 5.3 | 6.6 | 5.8 |
| 10 | 8.2 | 8.0 | 8.8 | 7.2 | 7.0 | 6.6 | 8.1 | 7.2 |
| 12 | 9.8 | -- | -- | 8.5 | 8.3 | 7.9 | 9.4 | 8.5 |

*2" loose soil above balloon
6" compacted soil below balloon

## Variation of Pressure with Depth in Hillsdale Sandy Loam in the Soil Box

The pressure measurements given in Figure 18 were made with the first model type A cells and not enough data were taken to establish reliable curves. The data are presented here to indicate how change in pressure with depth of confined soils might be determined with relatively few readings. The curves in Figure 18 were fitted to the data by linear regression and in all cases except the two-inch depth the curves crossed the zero line of pressure at the bottom of the box at an initial depth in the vicinity of 36 inches. Using 36 inches as the point of convergence and the pressure applied at the surface as a starting point, the lines were drawn as shown. The curves indicate that with this type soil at the given moisture content all of the load applied to the surface would be carried by the sides of the box when the depth reached approximately 36 inches with a reasonable applied load. If this assumption is true the convergence point for any soil at a given moisture could be determined by several duplications of a few points. Any of the needed curves could then be drawn. This assumption needs further investigation to draw definite conclusions.

Table VII and Figure 19 show the effect of applied pressure on the bulk density of Hillsdale sandy loam. It

FIG. 18. PRESSURE MEASUREMENTS IN HILLSDALE FSL

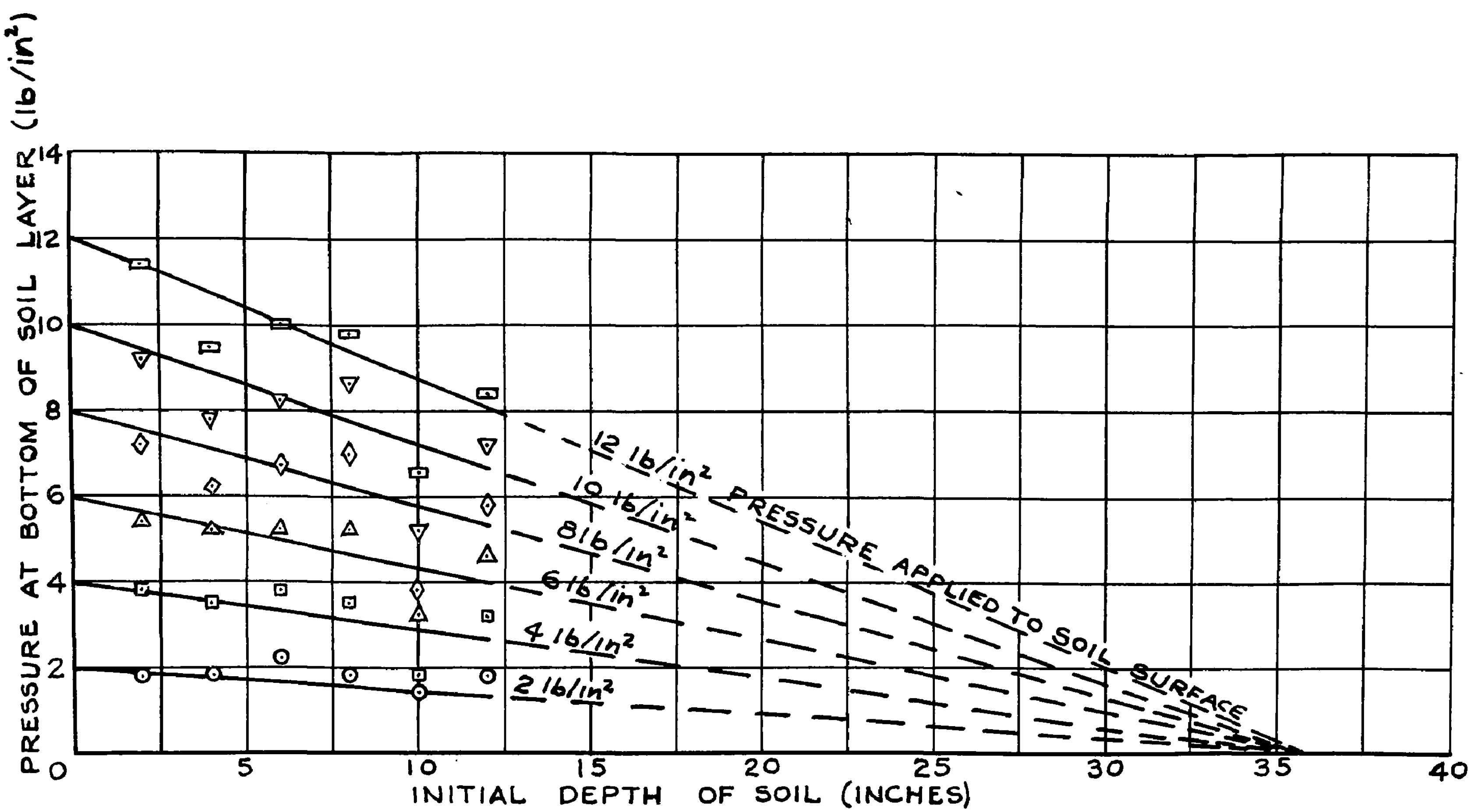


TABLE VII

EFFECT OF PRESSURE ON THE BULK DENSITY

OF HILLSDALE SANDY LOAM**

| Applied Pressure | Initial Depth of Soil (inches) | | | | | | Average |
|---|---|---|---|---|---|---|---|
| | 2 | 4 | 6 | 8 | 10 | 12 | |
| lb/in$^2$ | gm/cc | gm/cc | gm/cc | gm/cc | gm/cc | gm/cc | gm/cc |
| 0 | 0.90 | 0.93 | 0.92 | 0.93 | 0.93 | 0.93 | 0.92 |
| 2 | 1.06 | 1.09 | 1.05 | 1.07 | 1.05 | 1.08 | 1.07 |
| 4 | 1.12 | 1.16 | 1.14 | 1.15 | 1.12 | 1.14 | 1.14 |
| 6 | 1.20 | 1.20 | 1.18 | 1.20 | 1.18 | 1.18 | 1.19 |
| 8 | 1.24 | 1.26 | 1.22 | 1.24 | 1.20 | 1.23 | 1.23 |
| 10 | 1.28 | 1.28 | 1.24 | 1.27 | 1.24 | 1.30 | 1.27 |
| 12 | 1.28 | 1.30 | 1.26 | 1.30 | 1.27 | 1.34 | 1.29 |

*The various depths of soil were placed in the soil box and the pressures indicated were applied to each batch of soil. After each load was applied, the depth of the soil was recorded. The bulk density was calculated after determining the weight of the soil and the moisture content.

**The mechanical analysis of the Hillsdale sandy loam was 58.2% sand, 36.4% silt, and 5.4% clay.

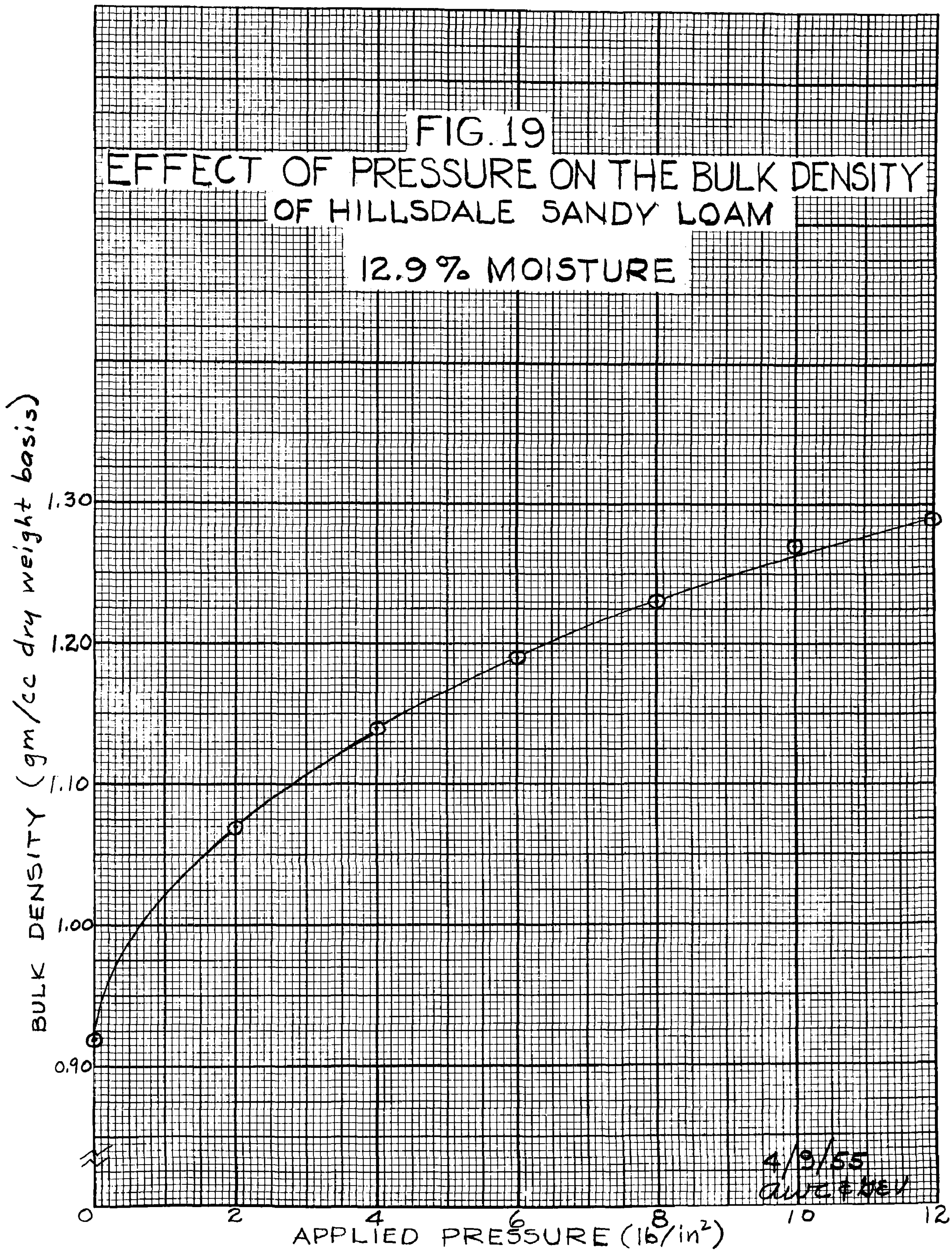


FIG. 19
EFFECT OF PRESSURE ON THE BULK DENSITY
OF HILLSDALE SANDY LOAM
12.9 % MOISTURE
BULK DENSITY (gm/cc dry weight basis)
1.30
1.20
1.10
1.00
0.90
0
2
4
6
8
10
12
APPLIED PRESSURE (lb/in²)
4/9/55

is surprising to note that the bulk density did not decrease when the depth of the soil was increased up to 12 inches.

## Measurement of Pressure at Various Depths Under the Rear Tire of a Tractor

The pressure measurements plotted in Figure 20 (except the 54 psi at zero distance below soil) were measured with type A pressure cells in Maumee sandy loam under the center of the rear tire of the Oliver 99 tractor at the Plowing Demonstration in Chicago in September 1955. The points, although scattered, give an indication of how the pressure in the soil decreases with depth under a surface load. The soil was very dense and entire weight of the tractor was carried on the lugs of the rear tires. The lugs penetrated the soil less than a quarter of an inch. Each rear tire carried about 4505 pounds and the area of the lugs in contact with the soil was 84 square inches, giving an average surface pressure of 54 psi. The tire inflation pressure was 16 psi. Each point represents a different pass of the tractor over the cells, so it is quite likely that the lugs were in a slightly different position, with respect to the cells each time which would cause a slight scatter of the point. Also since the average pressure applied to the surface was approximately 54 psi, the surface pressure just over the cell might have been slightly higher or lower than

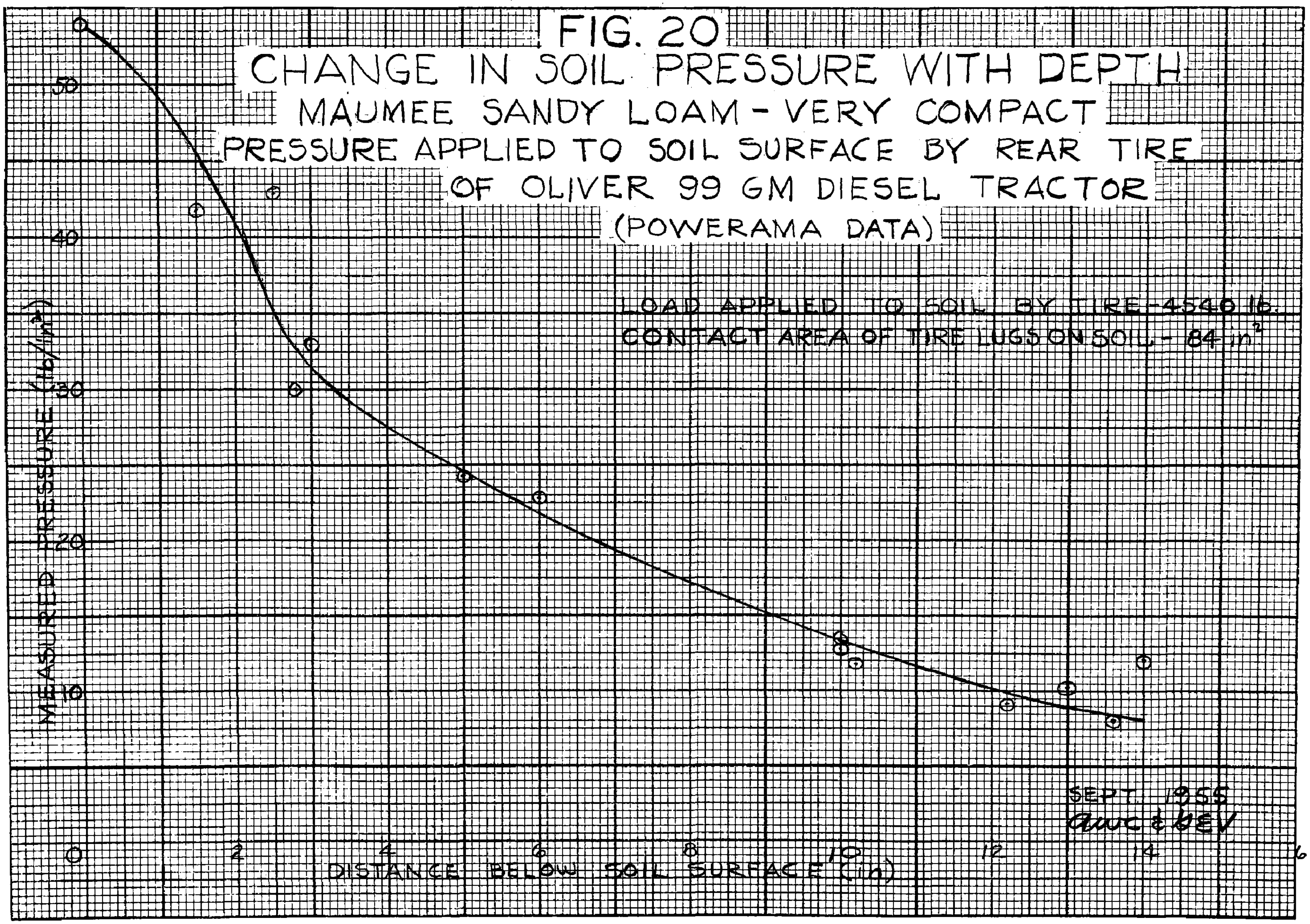


FIG. 20
CHANGE IN SOIL PRESSURE WITH DEPTH
MAUMEE SANDY LOAM - VERY COMPACT
PRESSURE APPLIED TO SOIL SURFACE BY REAR TIRE
OF OLIVER 99 GM DIESEL TRACTOR
(POWERAMA DATA)
LOAD APPLIED TO SOIL BY TIRE - 4540 lb.
CONTACT AREA OF TIRE LUGS ON SOIL - 84 in²
MEASURED PRESSURE (lb/in²)
50
40
30
20
10
0
2
4
6
8
10
12
14
16
DISTANCE BELOW SOIL SURFACE (in)
SEPT. 1955

the average. In any event the data line up in reasonable magnitude so that it can be concluded that the type A cell measures the pressure in the soil with a reasonable degree of accuracy.

## A Theoretical Discussion of the Effect of Load Area on Pressure in Soil at Various Depths Below the Surface

Figure 21 shows the pressures at various depths under the centers of three different diameter circular plates, uniformly loaded, as calculated by Froehlich's formula

$$\sigma_z = P_m \,(1 - \cos^4 \alpha)$$

where $\sigma_z$ = pressure at some distance under the load along the load axis,

$P_m$ = surface unit pressure, lb/in$^2$,

$\alpha$ = one-half the aperture angle between the point in question and the edge of the plate.

From the three curves using 18-inch, 12-inch, and 6-inch diameter plates, it can be seen that the pressure in the soil under the surface is not a function of the unit pressure alone but also depends on the total load applied to the surface of the soil.

It has been the common belief of many people that if one wants to reduce compaction in the soil all he has to do is to reduce the unit load applied to the soil and the pressure in the soil would be reduced proportionally. This is true for

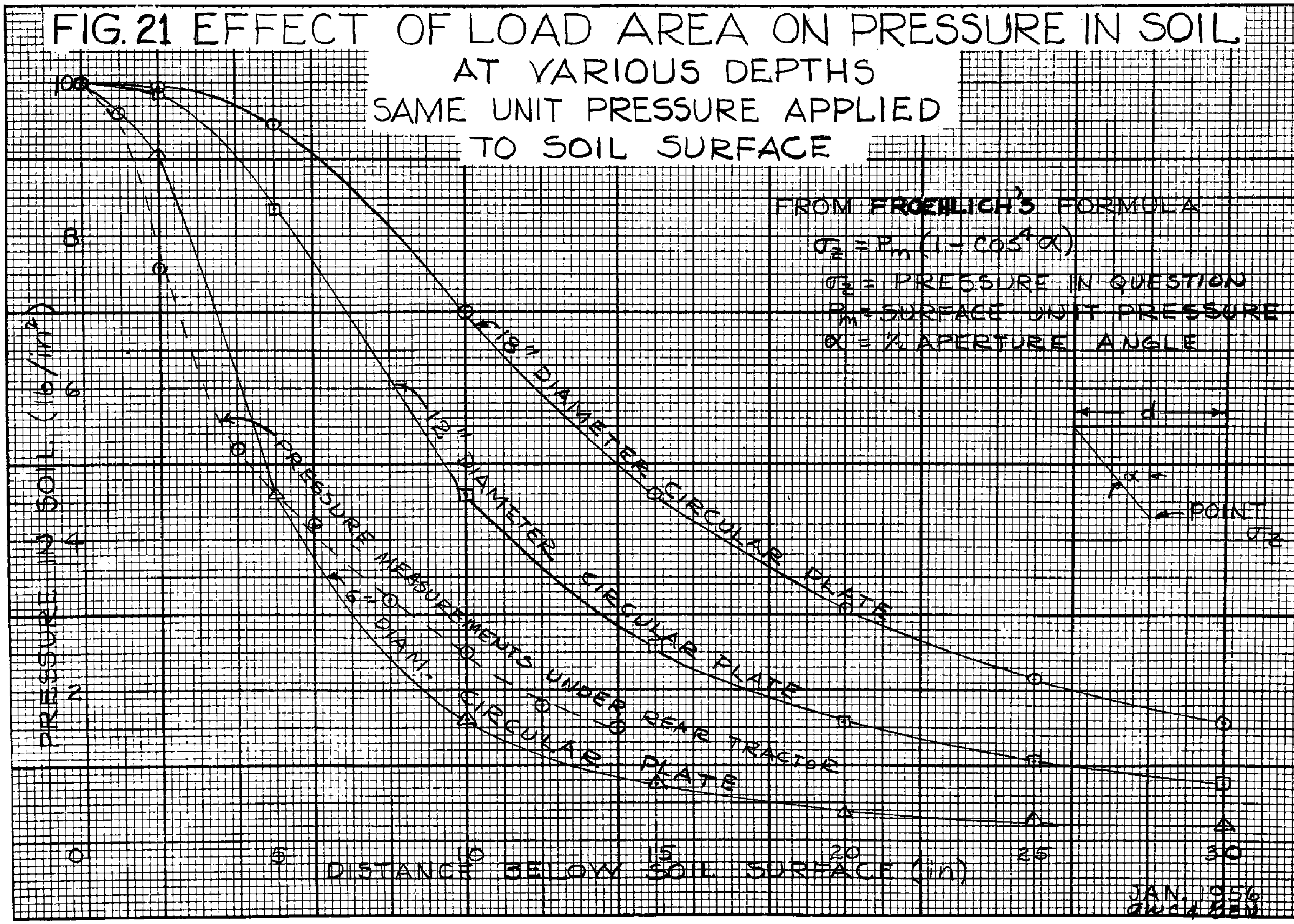



FIG. 21 EFFECT OF LOAD AREA ON PRESSURE IN SOIL AT VARIOUS DEPTHS
SAME UNIT PRESSURE APPLIED TO SOIL SURFACE

the surface pressure applied but is not true for the pressures in the soil (Figure 22). Both curves are for circular plates carrying the same total load. The 12-inch plate has exactly one-half the area of the 17-inch plate, thus it applies twice the unit load to the surface of the soil. As can be seen, with ten psi applied to the surface by the 12-inch plate, the pressure at 15 inches would be 2.6 psi, while with five psi applied to the surface by the 17-inch plate, the pressure in the soil at 15 inches would be 2.1 psi. While it helps some to double the area of contact surface of the tires of the tractor it does not reduce to one-half the compacting pressure in the soil below plowing depth.

It is interesting to note the shape of the curve of the measured pressure under the rear tractor tire in Figure 21. This is the same data as in Figure 20 with all the values divided by 5.4 to bring the data to the same unit surface pressure as the data calculated by Froehlich's formula. The shape of the contact surface of the tire was not a circle so the shape of the curves would not be expected to be identical.

Figure 23 represents the effect of bulk density and moisture content on the distribution of pressure in soils as calculated by Froehlich's formula. As explained by Soehne (33) a $\nu$-value of four represents a dense dry soil, a $\nu$-value of five represents a fairly moist relatively

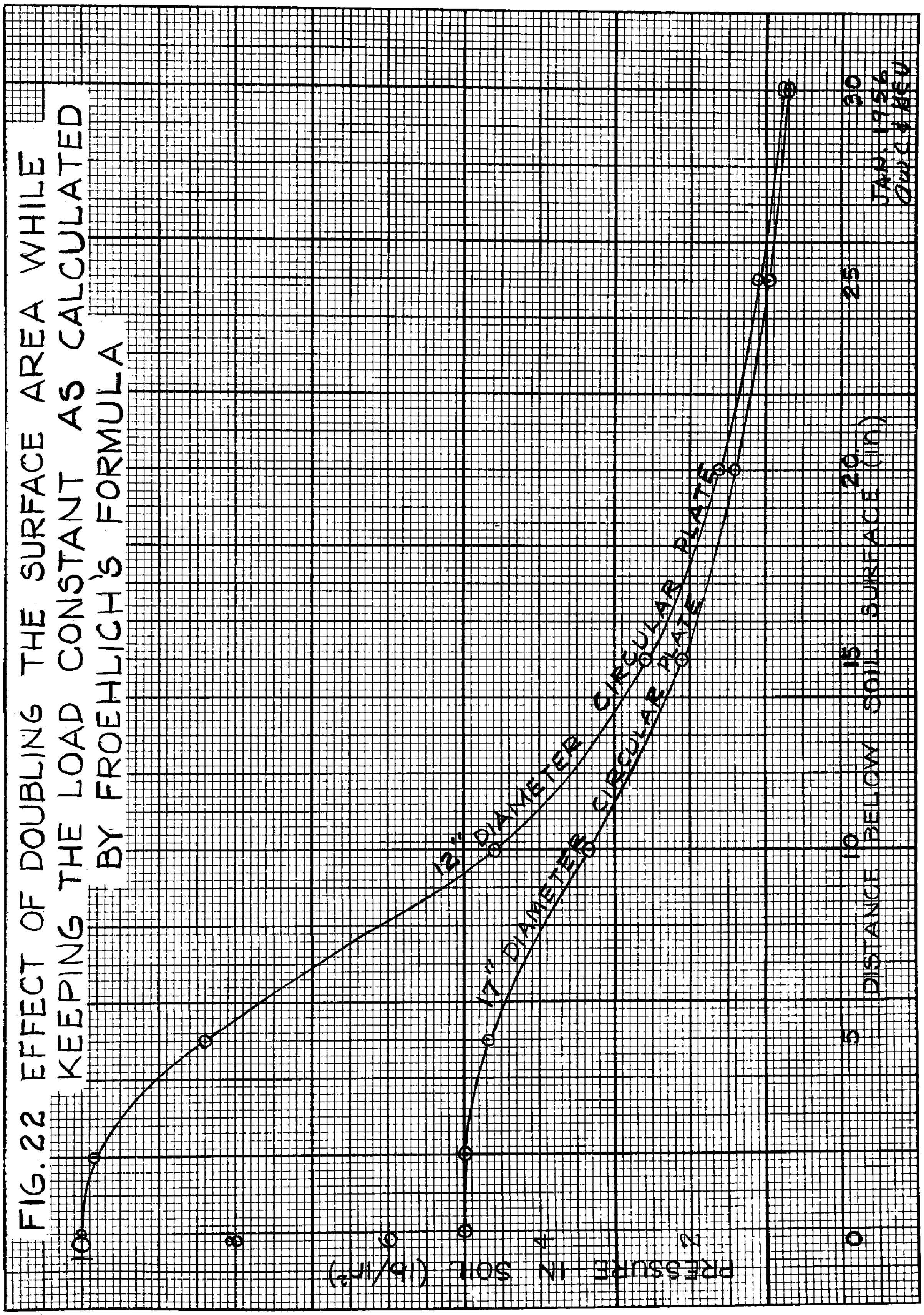



FIG. 22 EFFECT OF DOUBLING THE SURFACE AREA WHILE KEEPING THE LOAD CONSTANT AS CALCULATED BY FROEHLICH'S FORMULA

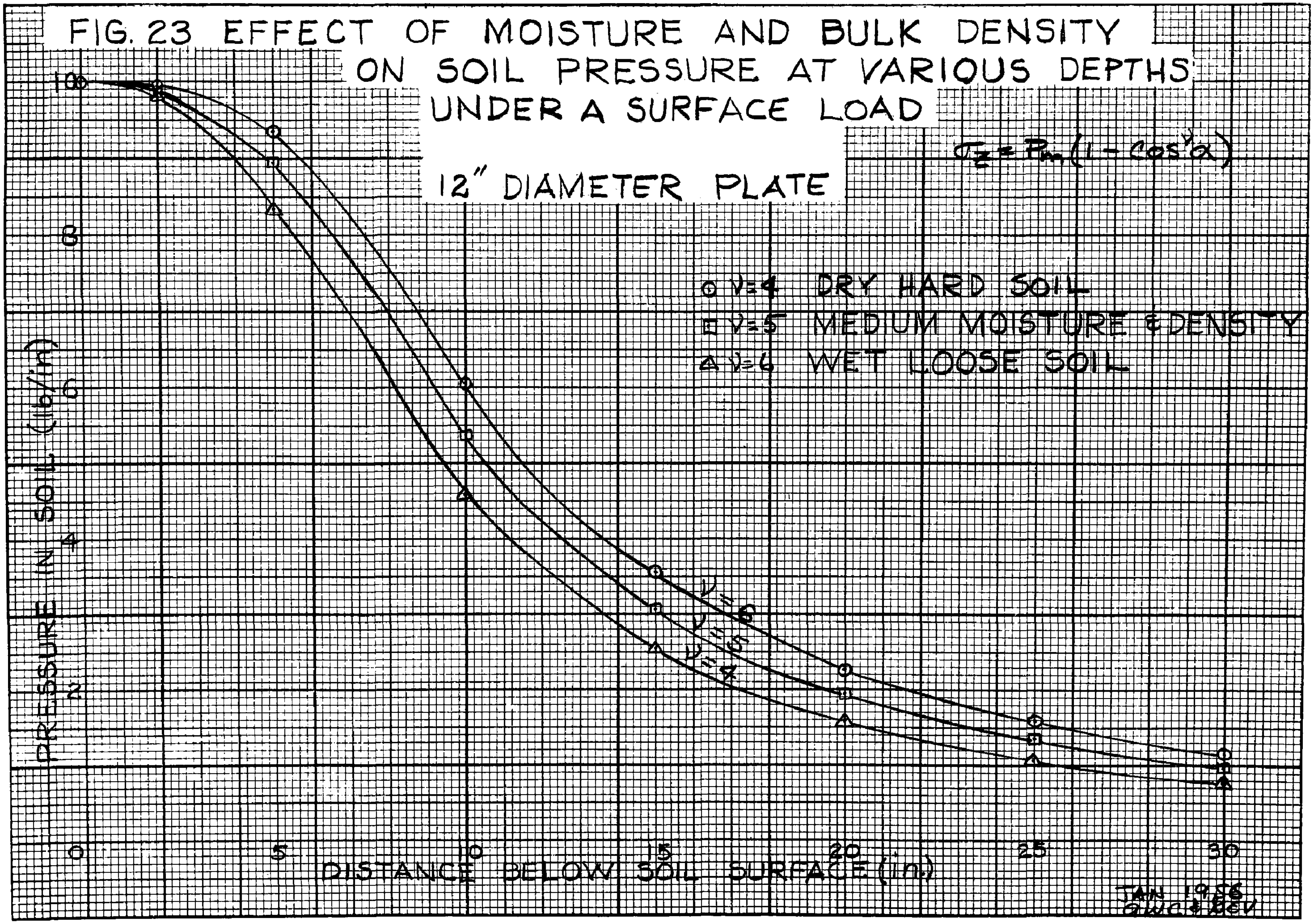



FIG. 23 EFFECT OF MOISTURE AND BULK DENSITY ON SOIL PRESSURE AT VARIOUS DEPTHS UNDER A SURFACE LOAD

12" DIAMETER PLATE

dense soil (about the proper condition for plowing), and a $\bar{\nu}$-value of six represents a wet soil or relatively loose soil. Soehne (33) gives a very good discussion of the effect of the size of tires and soil conditions on deformations of soil.

## RECOMMENDATIONS FOR FUTURE RESEARCH

1. Make further tests with the type A cells to determine their usefulness and limitations for measuring pressures in various textures of soil with various moisture contents and bulk densities.

2. Develop and test sensing bulbs for use with the liquid pressure transducer.

3. Develop a probe type measuring unit for studying the pressure distribution in field soils under various applied pressures. Could use information from 1 and 2.

4. Determine the effect of pressure on change in bulk density of soils of various types and at various moisture contents. These should be confined and unconfined soils.

5. Measure the total load and area of contact of various load applying units that operate in agricultural fields.

6. Measure the pressure distribution in various type soils at various moisture contents caused by agricultural traffic.

7. Create pressure pans and filter pans in various types of soil to study how they are formed.

8. Study methods of preventing induced pans.

9. Develop methods for loosening induced and genetic pans.

10. Study the effect of various shapes of tillage tools on the physical structure of soils.

11. Develop methods to determine the physical properties of soil before and after tillage tools are passed through them.

12. Determine the effect of plant root systems on force distributions in soil.

13. In cooperation with plant and soil scientists, determine methods for handling soils for optimum plant production.

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# APPENDIX

## TABLE VIII

## SAMPLE CALIBRATION DATA FOR TYPE A STRAIN GAGE PRESSURE CELL

| Pressure ($lb/in^2$) | Indicated Strain Reading (Two active gages) u in/in x 10 |
|---|---|
| 0 | 0 |
| 10 | 38.6 |
| 20 | 77.6 |
| 30 | 116.4 |
| 40 | 151.2 |
| 50 | 184.2 |
| 60 | 216.8 |
| 70 | 244.8 |
| 80 | 270.8 |
| 90 | 296.0 |

TABLE IX

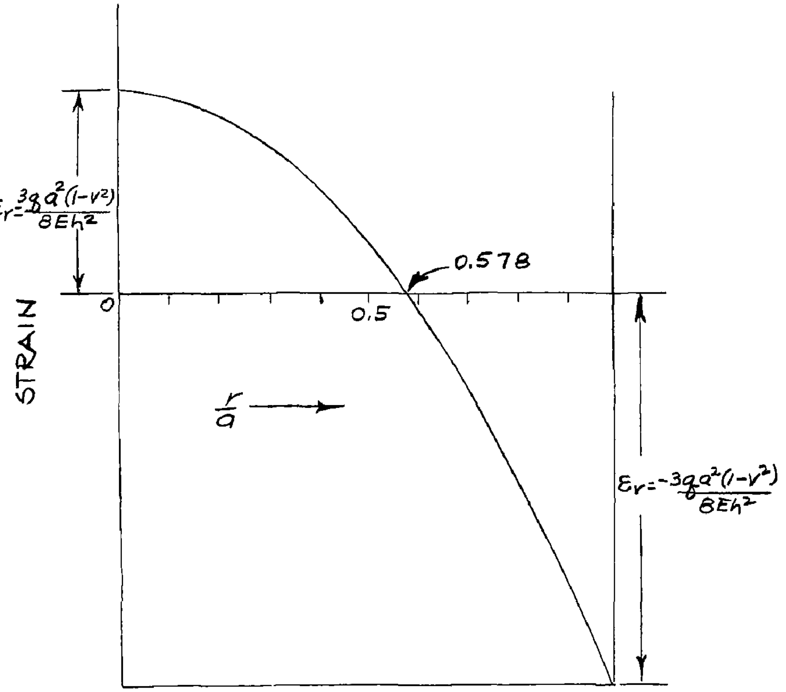
CHANGE IN SOIL PRESSURE WITH DEPTH

MAUMEE SANDY LOAM - VERY COMPACT[1]

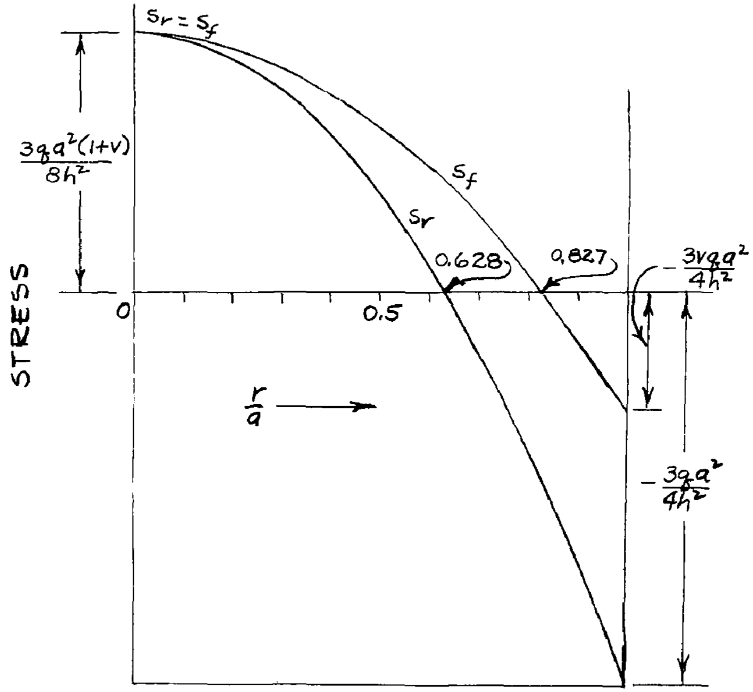
| Distance Below Soil Surface (in.) | Measure Pressure Under Center of Tire ($lb/in^2$) |
|---|---|
| 0* | 54.0 |
| 1.5 | 41.8 |
| 2.5 | 42.9 |
| 2.8 | 30.0 |
| 3.0 | 33.0 |
| 5.0 | 24.3 |
| 6.0 | 22.8 |
| 10.0 | 12.8 |
| 10.0 | 13.2 |
| 10.2 | 11.8 |
| 12.2 | 9.2 |
| 13.0 | 10.3 |
| 13.6 | 8.1 |
| 14.0 | 12.1 |

[1]Pressure applied to surface of soil by rear tire of Oliver 99 GM diesel tractor.

*Total load applied to soil by rear tractor tire - 4505 lb. Lug area of tire in contact with soil - 84 $in^2$.




DISTRIBUTION OF RADIAL STRAIN ON UNIFORMLY LOADED CIRCULAR DIAPHRAM WITH CLAMPED EDGES




VARIATION OF RADIAL AND TANGENTIAL STRESSES ALONG RADIUS OF UNIFORMLY LOADED CIRCULAR DIAPHRAGM WITH CLAMPED EDGES

NOTE: FROM U.S. WATERWAYS EXPERIMENT STATION REPORT (36)

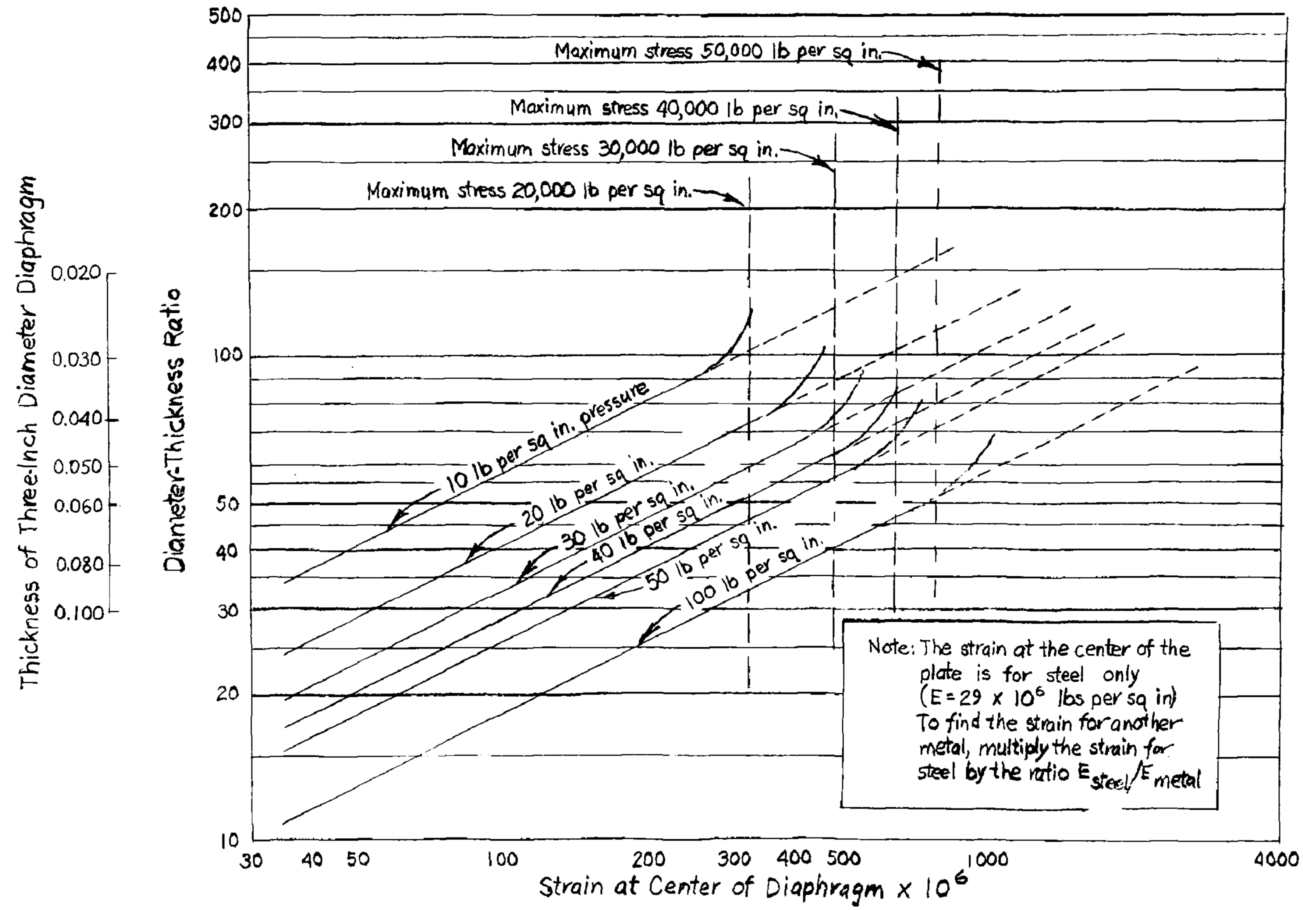
FROM: S. TIMOSHENKO IN "THEORY OF PLATES AND SHELLS" AND "STRENGTH OF MATERIALS - PART II"

LEGEND

$S_r$ = RADIAL STRESS = $\frac{6M_r}{h^2}$
$S_t$ = TANGENTIAL STRESS = $\frac{6M_t}{h^2}$
$M_r$ = RADIAL MOMENT = $\frac{q}{16}[a^2(1+\nu) - r^2(3+\nu)]$
$M_t$ = TANGENTIAL MOMENT = $\frac{q}{16}[a^2(1+\nu) - r^2(1+3\nu)]$

$q$ = MAXIMUM DESIGN PRESSURE
$a$ = RADIUS OF DIAPHRAGM
$\nu$ = POISSON'S RATIO
$r$ = DISTANCE FROM CENTER OF DIAPHRAGM
$h$ = THICKNESS OF DIAPHRAM
$\varepsilon_r$ = UNIT RADIAL STRAIN = $\frac{1}{E}(S_r - S_t)$
E = MODULUS OF ELASTICITY

FIG. 24
STRAIN AND STRESS DIAGRAMS




NOTE: FROM U.S. WATERWAYS EXPERIMENT REPORT (36)

FIG. 25

THEORETICAL STRESS AND STRAIN IN A UNIFORMLY LOADED CIRCULAR PLATE WITH CLAMPED EDGES

Circular flat plate, firmly secured all around the edge with load uniformly distributed over the unsupported area of the plate.

Machinery's Handbook, 14th Ed. Oberg and Jones, Reuleaux's formulas, p. 414.

W = total load in pounds

P = load in pounds per square inch

R = radius of plate, to the supporting edge, in inches

S = fiber stress in pounds per square inch

t = thickness of plate in inches

d = deflection at center of plate in inches

E = modulus of elasticity

$$W = 4.7\ St^2 \qquad S = 0.67\ \frac{PR^2}{t^2} = 0.21\ \frac{W}{t^2}$$

$$R = 1.22\ t\ \frac{S}{P} \qquad t = 0.81\ R\ \frac{P}{S} = 0.46\ \frac{W}{S}$$

$$P = 1.5\ \frac{St^2}{R^2} \qquad d = \frac{PR^4}{6Et^2} = 0.053\ \frac{WR^2}{Et^3}$$